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DETERMINATION OF THE FREQUENCY OF A PERIODIC PULSE BY A MOVING COIL GALVANOMETER

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(*Received 18 June 1970*)

Starting from the fundamental galvanometer equation, it has been shown that the ratio of galvanometer deflection for a full wavelength sinusoidal pulse to that due to a half wavelength pulse is proportional to the ratio of the period of the pulse to that of the galvanometer. Mathematically, this may be expressed as:

$$\frac{\theta_2}{\theta_0} = \pi \cdot \frac{\tau}{T}$$

where θ_2 is the maximum throw experienced by the galvanometer coil due to the incidence of a full period pulse; θ_0 corresponding deflection due to a half period pulse;

τ the period of the pulse expressed as $E = E_0 \sin \frac{2\pi}{\tau} t$;

and T the free period of the galvanometer coil.

The result has been verified experimentally using a mechanically operated pulse-generator.

Introduction

The torque acting on the coil of a d'Arsonval galvanometer is proportional to the direct current in the coil. For an alternating current of the type $I = I_{\max} \cos \omega t$, the galvanometer coil will be subject to a rapidly reversing torque, if $\omega \gg \omega_g$, where ω is the angular frequency of the coil and ω_g is the radian frequency of free motion of the coil.

However, the final deflection will be given by

$$\theta = (SI_m)(\omega_g/\omega)^2 \cos \omega t. \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

The first factor in parentheses is the deflection which would be obtained if a steady current I_m is passed through the coil. The factor $(\omega_g/\omega)^2$ therefore measures the ratio of the maximum deflection with the alternating current to the steady deflection of the direct current. If the supply frequency is 60 cycles/sec ($\omega = 377$/s) and the period of the galvanometer is 10 seconds ($\omega_g = 0{\cdot}63$/s), the reduction in sensitivity is by a factor of $3{\cdot}6 \times 10^5$. Hence, to all intents and purposes, the galvanometer shows no deflection on alternating currents.

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For alternating currents, therefore, the vibration galvanometer is sometimes employed at commercial frequencies. This is a modified d'Arsonval type instrument, which differs from the direct current galvanometer by having a moving system of very low moment of inertia and a very stiff suspension. The length of this suspension is adjustable allowing the torque per unit twist to be adjusted until the natural frequency of vibration is identical with the frequency of the applied alternating current.

The vibration galvanometer may also be made frequency selective by the series connection of a band pass or a low pass filter, either of which passes the fundamental frequency with little attenuation but discriminates strongly against harmonics.

Magnetic oscillographs, which employ d'Arsonval movements of short natural periods as their sensitive elements, were in use long before the cathode-ray oscilloscope was developed and still offer advantages over the newer instruments in some low frequency applications. A new method of determining the frequency of a L.F. sinusoidal alternating current with the help of an ordinary d'Arsonval galvanometer is described below.

MATHEMATICAL FORMULATION OF THE PROBLEM

The fundamental galvanometer equation is

$$MK^2\frac{d^2\theta}{dt^2}+\left(\frac{A^2H^2}{R}+\alpha\right)\frac{d\theta}{dt}+c\theta = AH\cdot\frac{E}{R} \quad \cdots \quad \cdots \quad (2)$$

where

t = time

MK^2 = moment of inertia of the coil including insulation and mirror

θ = angular distance of the coil from its position of equilibrium, measured in radians. θ is taken to be small so that $\sin\theta = \theta$

A = area of the coil, account being taken of the n number of turns

$AH\theta$ = total magnetic flux through the coil when displaced through a small angle θ

$AH\frac{d\theta}{dt}$ = back e.m.f. when the coil is rotating through an angular velocity $\frac{d\theta}{dt}$

R = resistance of the circuit

$\frac{A^2H^2}{R}\cdot\frac{d\theta}{dt}$ = retarding couple due to back e.m.f.

$\alpha\cdot\frac{d\theta}{dt}$ = retarding couple due to the air resistance (this could also be partly due to eddy currents induced in any metal parts attached to the moving system).

If the applied e.m.f. happens to be a periodic pulse of the form

$$E = E_0 \sin \frac{2\pi}{\tau} . t,$$

then the above equation (2) becomes

$$\frac{d^2\theta}{dt^2} + 2\mu\omega^2 . \frac{d\theta}{dt} + \omega^2 . \theta = \frac{AH}{MK^2} . i_0 . \sin \frac{2\pi}{\tau} t \qquad .. \qquad .. \qquad (3)$$

where

$$2\mu\omega^2 = \frac{1}{MK^2}\left(\frac{A^2H^2}{R} + \alpha\right);$$

$$\omega^2 = \frac{c}{MK^2} = \left(\frac{2\pi}{T}\right)^2;$$

$$i_0 = E_0/R.$$

T = free period of the galvanometer

and

τ = period of the pulse.

The solution of the above equation (3) under the initial conditions $\theta = 0$ and $\frac{d\theta}{dt} = 0$ is

$$\theta = B . e^{-\mu\left(\frac{2\pi}{T}\right)^2 . t} . \cos\left(\frac{2\pi}{T} . \sqrt{1-\mu^2\omega^2} . t + \epsilon\right)$$

$$+ \frac{AH . i_0}{c} . \frac{\sin\left[\frac{2\pi}{\tau} . t - \tan^{-1}\left\{2\mu\left(\frac{2\pi}{\tau}\right) \Big/ \left(1 - \frac{T^2}{\tau^2}\right)\right\}\right]}{\left[\left(1 - \frac{T^2}{\tau^2}\right)^2 + 4\mu^2\left(\frac{2\pi}{\tau}\right)^2\right]^{\frac{1}{2}}} \qquad .. \qquad (4)$$

where

$$\epsilon = \tan^{-1} \frac{\left(1 - \frac{T^2}{\tau^2}\right) - 2\mu^2\left(\frac{2\pi}{T}\right)^2}{2 . \left(\frac{2\pi}{T}\right) . \mu\left[1 - \mu^2\left(\frac{2\pi}{T}\right)^2\right]^{\frac{1}{2}}}$$

and

$$B = \frac{AHi_0}{c} . \frac{2\mu\left(\frac{2\pi}{\tau}\right)}{\left(1 - \frac{T^2}{\tau^2}\right)^2 + 4\mu^2\left(\frac{2\pi}{\tau}\right)^2} \sec \epsilon.$$

This solution holds for the case $\mu\omega < 1$. If T be large enough such that any term involving $\left(\frac{2\pi}{T}\right)^2$ is negligible in comparison to the other terms, then

$$\epsilon = \tan^{-1} \frac{1 - \frac{T^2}{\tau^2}}{2\mu\left(\frac{2\pi}{T}\right)}$$

and

$$B = \frac{AHi_0}{c} \cdot \frac{\frac{T}{\tau}}{1 - \frac{T^2}{\tau^2}}.$$

Hence the solution (4) reduces to

$$\theta = \frac{AHi_0}{c\left(1 - \frac{T^2}{\tau^2}\right)} \cdot \left[-\frac{T}{\tau} \cdot \sin\left(\frac{2\pi}{T} t - \tan^{-1} \frac{2\mu\left(\frac{2\pi}{T}\right)}{1 - \frac{T^2}{\tau^2}} \right) \right.$$

$$\left. + \sin\left(\frac{2\pi}{\tau} t - \tan^{-1} \frac{2\mu\left(\frac{2\pi}{\tau}\right)}{1 - \frac{T^2}{\tau^2}} \right) \right].$$

Now

$$\tan^{-1} \frac{2\mu\tau^2\left(\frac{2\pi}{T}\right)}{\tau^2 - T^2} \approx \tan^{-1}\left(-\frac{4\mu\pi\tau^2}{T^3} \right),$$

which is negligible in comparison to $\frac{2\pi}{T} t$;

and

$$\tan^{-1} \frac{2\mu\left(\frac{2\pi}{\tau}\right)}{1 - \frac{T^2}{\tau^2}} \approx \tan^{-1}\left[-\frac{2\mu(2\pi\tau)}{T^2} \right],$$

which is negligible in comparison to $\frac{2\pi}{\tau} t$.

Thus

$$\theta = \frac{AHi_0}{c\left(1 - \frac{T^2}{\tau^2}\right)} \left[\sin \frac{2\pi}{\tau} t - \frac{T}{\tau} \cdot \sin \frac{2\pi}{T} t \right] \quad \ldots \quad \ldots \quad (5)$$

and

$$\frac{d\theta}{dt} = \frac{2\pi \cdot AHi_0}{\tau \cdot c \cdot \left(1 - \frac{T^2}{\tau^2}\right)} \left[\cos \frac{2\pi}{\tau} t - \cos \frac{2\pi}{T} t \right]. \quad \ldots \quad \ldots \quad (6)$$

If the galvanometer experienced a single half pulse, θ would become θ_1 at the end of the time, where

$$\theta_1 = \frac{2\pi \cdot AHi_0}{\tau c \left(\frac{T^2}{\tau^2} - 1 \right)} \left[1 + \cos \pi \cdot \frac{\tau}{T} \right] \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (7)$$

and its deflection θ_1 would be

$$\theta_1 = \frac{AHi_0}{c\left(\frac{T^2}{\tau^2}-1\right)}\left[\frac{T}{\tau}\cdot \sin\left(\pi \cdot \frac{\tau}{T}\right)\right]. \qquad \cdots \qquad \cdots \qquad \cdots \qquad (8)$$

The throw would continue beyond θ_1, to the extent θ_0 given by the energy equation

$$\tfrac{1}{2} MK^2 \cdot \dot{\theta}_1^{\,2} = \tfrac{1}{2} c(\theta_0^{\,2}-\theta_1^{\,2}) \qquad \cdots \qquad \cdots \qquad \cdots \qquad (9)$$

or

$$\left(\frac{T}{2\pi}\right)^2 \cdot \dot{\theta}_1^{\,2}+\theta_1^{\,2} = \theta_0^{\,2}. \qquad \cdots \qquad \cdots \qquad \cdots \qquad (10)$$

Therefore,

$$\theta_0^{\,2} = \left[\frac{AHi_0}{\frac{T^2}{\tau^2}-1}\right]^2 \cdot \frac{T^2}{c^2\tau^2}\left[1+\cos \pi \frac{\tau}{T}\right]^2$$

$$+\left[\frac{AHi_0}{\frac{T^2}{\tau^2}-1}\right]^2 \cdot \frac{T^2}{c^2\tau^2} \cdot \sin^2 \pi \cdot \frac{\tau}{T} \qquad \cdots \qquad \cdots \qquad \cdots \qquad (11)$$

or

$$\theta_0 = 2^{\frac{1}{2}} \cdot \left[\frac{AHi_0}{\frac{T^2}{\tau^2}-1}\right] \cdot \frac{T}{c\tau}\left[1+\cos \pi \cdot \frac{\tau}{T}\right]^{\frac{1}{2}}. \qquad \cdots \qquad \cdots \qquad (12)$$

If the pulse had continued for one complete period and no more, we should have as follows:

we seek a maximum for eqn. (5) by putting $\frac{d\theta}{dt} = 0$

i.e. $$\cos\frac{2\pi t}{\tau} - \cos\frac{2\pi t}{T} = 0.$$

Hence, either

$$\frac{2\pi t}{\tau} - \frac{2\pi t}{T} = 2\pi n_0 \qquad \cdots \qquad \cdots \qquad \cdots \qquad \cdots \qquad (13)$$

or

$$\frac{2\pi t}{\tau} = 2\pi n_0 - \frac{2\pi t}{T} \qquad \cdots \qquad \cdots \qquad \cdots \qquad \cdots \qquad (14)$$

where n_0 is any positive integer.
From eqn. (13), we get

$$t_{\max} = \left(\frac{T\tau}{T-\tau}\right) \cdot n_0$$

while from eqn. (14), we get

$$t_{\max} = \frac{n_0 T\tau}{T+\tau}.$$

The maximum which occurs for $t < \tau$ is that for

$$t_{\max} = \frac{T\tau}{T+\tau} \quad (\text{taking } n_0 = 1),$$

then from eqn. (5)

$$\theta_2 \doteq \frac{AHi_0}{c\left(\frac{T^2}{\tau^2}-1\right)}\left[-\sin\frac{2\pi T}{T+\tau}+\frac{T}{\tau}\sin\frac{2\pi\tau}{T+\tau}\right].$$

Therefore,

$$\frac{\theta_2}{\theta_0} = \frac{\sin\frac{2\pi\tau}{T+\tau}-\frac{\tau}{T}\cdot\sin\frac{2\pi T}{T+\tau}}{2^{\frac{1}{2}}\left[1+\cos\pi\frac{\tau}{T}\right]^{\frac{1}{2}}}.$$

$$= \frac{2\pi\cdot\frac{\tau}{T}}{2}$$

$$= \pi\cdot\frac{\tau}{T} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (15)$$

since $\left(\frac{\tau}{T}\right)^2$ is negligibly small.

EXPERIMENTAL ARRANGEMENT

The experimental arrangement is simple and diagrammatically represented in Fig. 1.

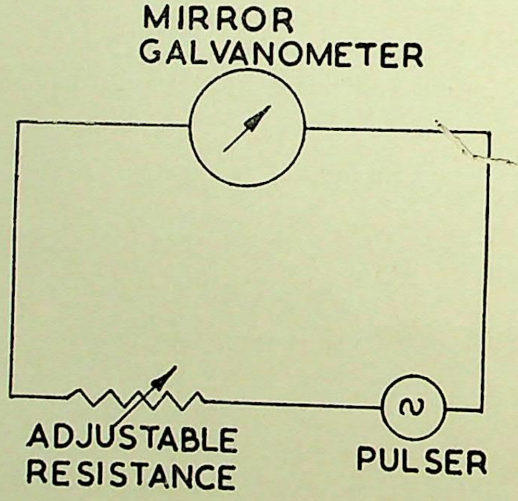

FIG. 1. Galvanometer circuit

It consists essentially of a ballistic galvanometer with known constants, a series resistor and a mechanical pulser. A single full pulse or a half pulse can be injected into the circuit and the corresponding throws of the galvanometer spot of light is recorded.

Pulse generator

A laboratory demonstration type A.C. dynamo was initially used to produce the required pulses. It consisted of a coil rotated by some external mechanical power, between the two poles of a horse-shoe magnet. The induced voltage generated in the coil can be led outside by slip rings and behaves as an alternating source of current. Unfortunately due to malfunctioning of the slip-ring contacts, pure sinusoidal waveform was difficult to obtain. And so, a commercial-type cycle dynamo was used instead, which consisted of a fixed coil and a rotating system of permanent magnets. The dynamo unit is shown in Fig. 2.

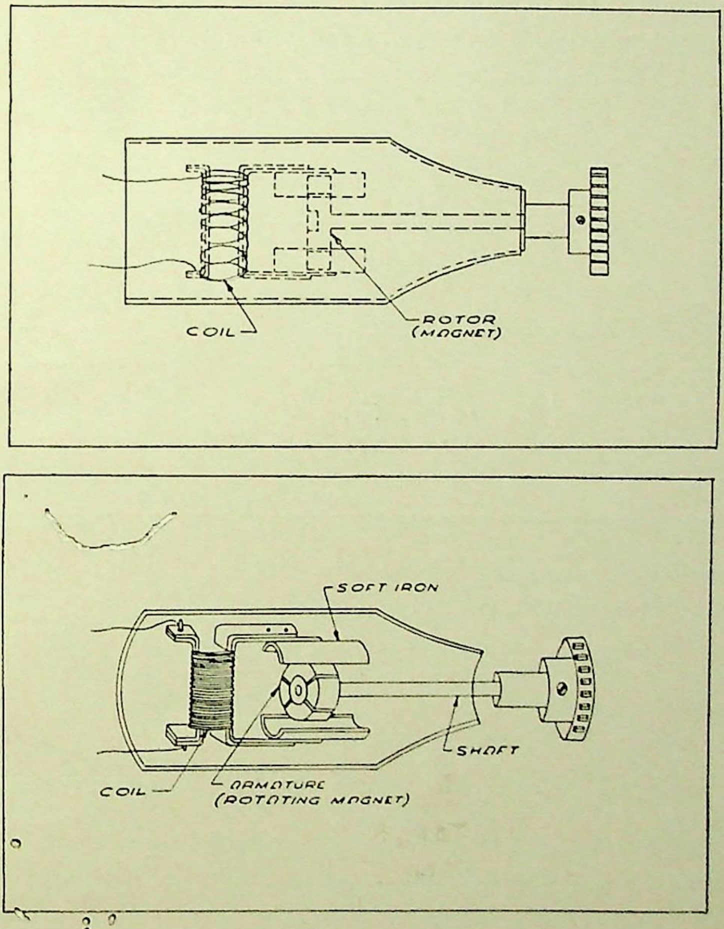

FIG. 2. Pulse generator

The period of the sinusoidal pulse depending upon the speed of rotation of the magnets could be conveniently adjusted by an array of gears having predetermined ratios. The time-duration for a half pulse or a full pulse could also be accurately controlled by means of suitable stops in the driving mechanism. The time-period of the pulses are checked and calibrated with the help of a cathode-ray oscillograph.

EXPERIMENTAL RESULTS

It may be seen from equation (15) that

$$\tau = \frac{T}{\pi} \cdot \frac{\theta_2}{\theta_0}$$

where

τ = period of the injected sinusoidal pulse
T = period of the galvanometer
θ_2 = maximum deflection due to a full period pulse
θ_0 = corresponding deflection due to a half period pulse.

Table I shows a typical set of data for a particular setting of the pulse generator.

TABLE I

No. of measurement	Galvanometer deflection in cm		Mean deflection for half pulse θ_0 (cm)	Mean deflection for full pulse θ_2 (cm)
	Full pulse	Half pulse		
1	1·3	18·7	18·47	1·33
2	1·4	18·4		
3	1·3	18·4		
4	1·3	18·4		

Free period of galvanometer used, $T = 7 \cdot 14$ sec.
Therefore, frequency of the pulse

$$= \frac{1}{\tau} = \frac{\pi}{T} \cdot \frac{\theta_0}{\theta_2} = \frac{\pi}{7 \cdot 14} \times \frac{18 \cdot 47}{1 \cdot 33}$$

$$= 6 \text{ cycles/sec.}$$

Actual frequency of the sinusoidal pulse generated by the pulse generator and checked by C.R.O. = 6 cycles per second.

ACKNOWLEDGEMENTS

We wish to pay homage to the memory of the late Dr. W. F. G. Swann, Director, Bartol Research Foundation, Swarthmore, Pa, U.S.A., who initially suggested the galvanometer problem.

One of us (A. K. G.) is grateful to the University Grants Commission for the award of a research scholarship.

PUNJABITHERIUM gen. nov.

AN EXTINCT RHINOCEROTID OF THE SIWALIKS, PUNJAB, INDIA

by Ehsanullah Khan,* *Department of Geology, Aligarh Muslim University, Aligarh*

(Communicated by F. C. Auluck, F.N.A)

(*Received 25 October 1970; after revision 16 February 1971*)

The discovery of a new rhinocerotid skull, containing two incisors, from the lower bed of the Upper Siwaliks, furnishes sufficient data to establish a new genus. Establishing a new genus, for want of definite evidence as to the presence of the incisors, has been a long-pending problem. Comparison has been made with related genera, and conflicting opinions of earlier workers have been discussed.

Introduction

Baker and Durand collected a rhinocerotid skull (Brit. Mus. No. 3661, Falconer 1868) in the vicinity of the Jamuna River (30° 80′; 77° 40′) and some partial skulls and rami were collected by Falconer and Cautley (1847) from the same locality, and referred these fossils to *Rhinoceros platyrhinus*. Not even a single tooth of this rhinoceros was unearthed from the Siwaliks of the Salt Range and adjacent areas. Perhaps this is why Lydekker (1881) remarked that this species may be confined to 'the typical Siwaliks near the Ganges and Jamuna'. The skull collected by Baker and Durand did not contain the premaxillae, and naturally there was no definite evidence of the presence or absence of the incisors.

Although it was suggested that *Rhinoceros platyrhinus* F. and C. might have been the ancestor of *Coelodonta antiquitatis* (Blumenbach) or might have been related to *Rhinoceros deccanensis* Lyd. (Matthew 1929), yet such characters as the absence of the nasal septum, and the presence of complex molar structures, two horn-pads and the union of the postglenoid and posttympanic processes of the squamosals below the external auditory meatus in *R. platyrhinus*, do not wholly agree with the characters of other genera of Rhinocerotidae. Consequently, Lydekker (1881), Matthew (1929, 1931) and Colbert (1935) agreed in favour of referring it to a separate genus, or at least to a subgenus. The discovery of the present skull in which two incisors are present provides adequate data for assigning the specimen to a new genus, herein named

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Punjabitherium, which name would now be applicable also to the fossil remains originally referred to *Rhinoceros platyrhinus*.

Description

Order	PERISSODACTYLA Owen, 1848
Family	**Rhinocerotidae** Gray, 1910
Subfamily	RHINOCERINAE
Genus	*Punjabitherium* gen. nov.

Punjabitherium platyrhinum (Falconer et Cautley)

Pl. VI, figs. 1–4

Rhinoceros platyrhinus, Falconer and Cautley 1847, Pl. 72, figs. 1–7; Pl. 75, figs. 9–12.

Dicerorhinus platyrhinus, Pilgrim 1910, p. 201.

Coelodonta platyrhinus, Matthew 1929, pp. 444, 534–535.

Coelodonta platyrhinus, Colbert 1935, pp. 178–179.

Diagnosis—A large bicorn rhinocerotid; skull without nasal septum; postglenoid and posttympanic processes of the squamosals united below the external auditory meatus; inclination of occiput backward; premaxilla with two incisors; cheek teeth hypsodont with well-developed crochet and crista.

Locality—A little over 3 kilometres north-east of Gurha Village (about 11 kilometres NNW of Chandigarh), No. A/559 (Geol. Dept., Panjab Univ., Chandigarh).

Horizon—Upper Siwaliks, near the base of the Pinjor stage.

Collected by—Ehsanullah Khan.

State of preservation—The skull is well preserved except for the upper part of occiput, tip of the nasals and teeth (only last molars are present). The skull is slightly pressed from right to left.

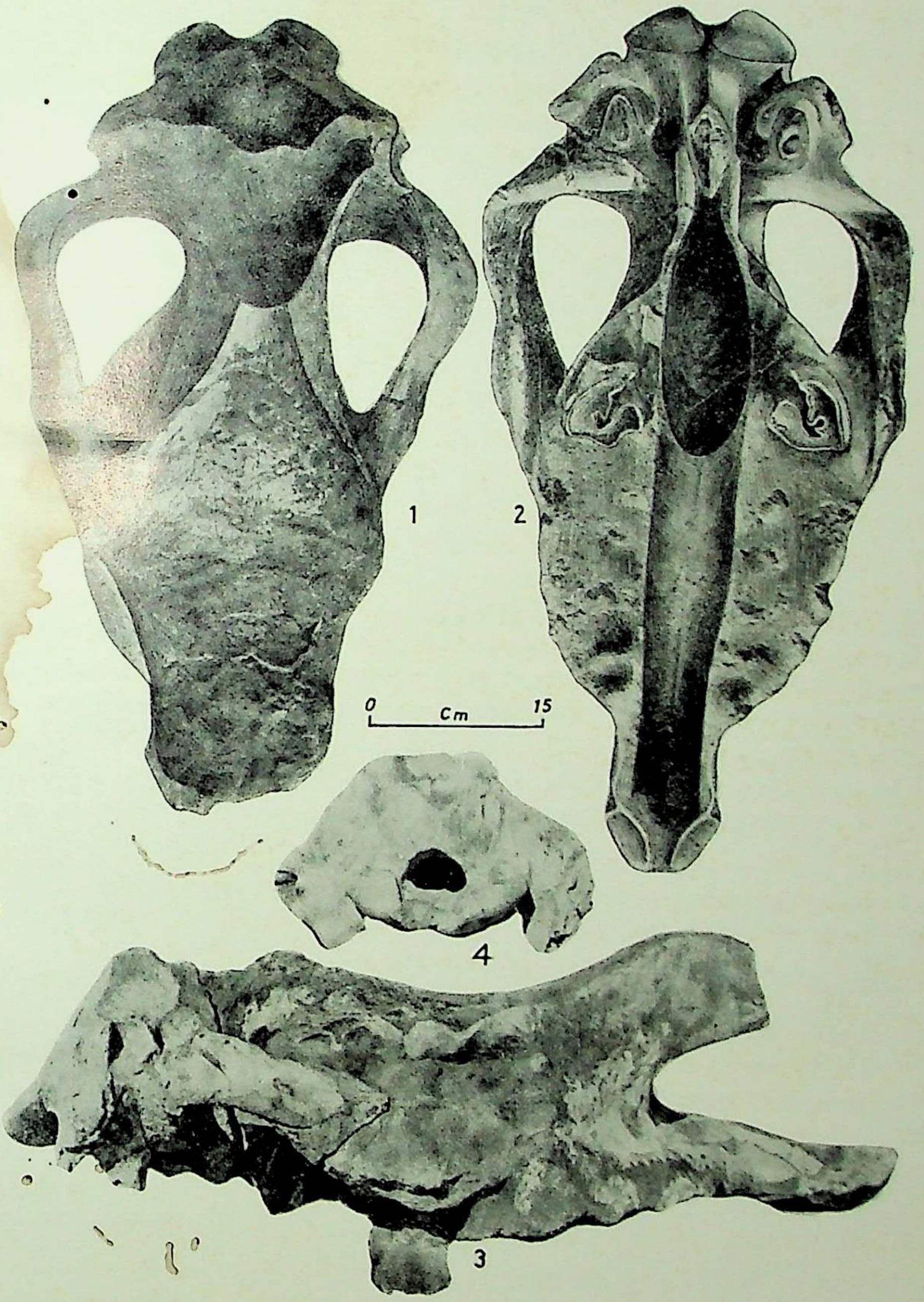
Lectotype—Brit. Mus. No. 33662, a battered skull.

Neotype—Brit. Mus. No. 36661, a nearly complete skull.

COMPARISON WITH TYPE (NEOTYPE) SPECIMEN

The sutures are obliterated, since the skull belongs to an old individual. Therefore, the individual bones cannot be compared and described precisely. However, a thorough comparative study of the present skull with the neotype reveals the following differences:

In the cast of the neotype specimen (No. C. 64, in the Geological Survey of India, Calcutta) a prominent ridge joins the anterior and posterior elevated rough surfaces, which are the platforms for the attachment of the horns. This ridge and posterior elevated surface are not traceable in the present skull, perhaps due to compression. Also, the skull is narrower in the occipital region and, in general, broader and shorter than the neotype; the former belongs to an old individual and the latter (neotype) to a young one.



FIGS. 1 to 4. *Punjabitherium platyrhinum*, Pinjor stage, Punjab, India, Panj. Univ. No. A/559. 1, top view of the skull (photograph retouched); 2, palatal view of the same (photograph retouched); 3, lateral view of the same; 4, occipital view of the same.

COMPARISON WITH OTHER GENERA

Punjabitherium differs from *Dicerorhinus* in its complex cheek teeth structures and union of postglenoid and posttympanic processes of the squamosal below the external auditory meatus; from *Coelodonta* in the absence of the supporting nasal septum; from *Diceros* and *Ceratotherium* in the well-developed premaxillae with two incisors.

TABLE I

Comparison: Measurements in Millimetres

	Present skull No. A/559	Lyd. 1881, p. 49 Neotype, C 64	Lyd. 1881, p. 49 Cotype and Paratype
Length from inferior border of foramen magnum to tip of premaxillae	762·00	749·30(29·5)	—
Greatest width across zygomae	396·20	373·40(14·7)	—
Length of six molars	297·20	317·50(12·5)	—
Interval between outer surface of penultimate molars	248·90	213·40(8·4)	—
Height of occiput from inferior margin of foramen magnum	—	304·80(12·0)	304·80(12·0)
Width of occiput above	—	218·40(8·6)	213·40(8·4)
Width of occiput below	279·40	337·80(13·3)	335·30(13·2)
Height of foramen magnum	60·90	63·50(2·5)	63·50(2·5)
Width of foramen magnum	50·80	53·30(2·1)	50·80(2·0)
Interval between external angles of occipital condyles	147·30	152·40(6·0)	134·60(5·3)
Extreme length of cranium following curves of upper surface	685·80	838·20(33·0)	—
Greatest width at orbits	278·80	264·20(10·4)	269·20(10·6)
Width of nasals	137·20	152·40(6·0)	—
Length of i^1	55·90	—	—
Width of i^1	30·50	—	—
Length of i^2	15·20	—	—
Width of i^2	12·70	—	—

Even if there is doubt about the presence of a second horn-pad, the greater length and width of the skull of *Punjabitherium* clearly distinguish it from the three species of *Rhinoceros*: *R. sivalensis*, *R. palaeindicus* and *R. unicornis*.

REMARKS

The differences in the dimensions of the skull and the type (neotype) is due to the difference in sex and age. The skull belongs to an old female individual and the type one (neotype) is of a young male.

Discussion

Lydekker (1881) distinguished *Rhinoceros platyrhinus* from *Dicerorhinus sumatrensis* by the union of postglenoid and posttympanic processes of the squamosals below the external meatus, whereas Pilgrim (1910) recognized *Rhinoceros platyrhinus* as *Dicerorhinus platyrhinus* without giving any reason, Matthew (1929) recognized this species as of *Dicerorhinus*, but later (1929), on the characters of the cheek teeth, preferred to change this decision. He (1929) compares the characters of *R. platyrhinus* with those of other related genera but does not commit himself definitely. Colbert (1935) states that in *R. platyrhinus* F. and C., the postglenoid and posttympanic processes of the squamosals are separate and the external auditory meatus opens below. However, close observations reveal that in the present skull assigned to *Punjabitherium* these processes are not completely fused together as in *Rhinoceros sondaicus*, but they are certainly united (Pl. VI, fig. 3); nor are they separate as in *Dicerorhinus sumatrensis*.

Remains of *R. sivalensis*, *R. palaeindicus* and *P. platyrhinum* are found in the Pinjors, but it does seem reasonable that more than one species of the same genus may exist simultaneously in the same environment of a particular place. It is, therefore, probable that *R. sivalensis* and *R. palaeindicus* are synonymous, since they are almost of the same dimension, and the variation in the structure of the cheek teeth and the shape of skull may be attributed to age or sex, whereas considerably greater length and width of the skull (a feature which does not lie within the limit of species variation even after considering the age and sex), and the presence of two horn-pads, provide adequate data for recognizing *Punjabitherium* as a distinct genus.

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THE ROLE OF PALAEONTOLOGY IN THE STUDY OF THE PLEISTOCENE

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The knowledge of mammalian palaeontology can be utilized to solve chronological problems related to Early Man, his tools and cultures.

Introduction

Archaeologists study man, his cultures and the tools which he prepared in the various environments in which he lived during prehistoric times. He invented numerous techniques for preparing tools which properly matched these environments. Thus, for a thorough understanding of the development of these various techniques for tool-making, a study of the environments in which Early Man lived is needed (the environment is the sum total of the interrelationships of the biota (fauna and flora), climate, soil, rock and morphology of the region). These techniques also need to be investigated to learn if they evolved gradually in different parts of the world or whether they developed simultaneously, side by side, in the same region. Palaeontological and radiometric methods are very helpful in solving chronological problems. Thus, the field of archaeology is, today, so broad that it can only be studied by a group of scholars specializing in different branches such as mentioned above. The present paper shows how the knowledge of mammalian palaeontology can help to determine the geological age of Pleistocene deposits in which tools may occur.

Historical Resume

It is appropriate to start the study of the Indian Pleistocene with the work of De Terra and Paterson (1939) who gave a comprehensive account, including the study of glaciation, terrace formation, fluvo-lacustrine deposits, and the fauna including Early Man and his tools. According to these authors, the beginning of the Pleistocene, which is synchronous with the commencement of the first glaciation, is recognized in India at the base of the Tatrot beds, and this view is still held by many Indian archaeologists and palaeobotanists. Geologists revised this view at the 18th International Geological Congress held in Great Britain (1948) and agreed that the Blancan (U.S.A), Villafranchian (Europe), Pinjaurs (India) and Djetis beds (Java) equivalently marked the beginning of the Pleistocene. Later, by a detailed study of the fauna and lithology of the Upper Shivaliks, east of Chandigarh, it was recognized that the Lower Boulder Conglomerate is equivalent to the Gunz (Sahni and Khan 1964).

GEOLOGICAL RANGE OF THE INDIAN PLEISTOCENE MAMMALIAN FAUNAS

The Shivalik Hills and Narmada Valley are famous for mammalian remains of the Indian Pleistocene. Until recently it was a general view that the remains of mammalian faunas had been found in India throughout the entire Pleistocene without a faunal break. These mammalian faunas were considered to have occurred in the Lower Pleistocene in the Shivaliks and in the Middle and Upper Pleistocene in the Narmada alluvial deposits. The author (Khan 1968) is of the view that almost all the mammalian remains recovered from the Narmada alluvial deposits belong to the last interglacial

SPECIES AND THEIR GEOLOGICAL RANGES

Species	Upper pliocene	Pleistocene			
	Tatrot	Pinjaur	1st to 3rd Glacial	3rd Inter-glacial	4th Glacial
PRIMATES—					
Papio sub-himalayanus	....	....			
Presbytis sivalensis			?........		
Presbytis entellus					....
CARNIVORA—					
Mellivora sivalensis		....			
Ursus namadicus				....	
Crocuta sivalensis	....	....			
Hyaena crocuta					....
PROBOSCIDEA—					
Stegodon insignis-ganesa	....	....			
Stegodon pinjorensis		....			
Stegodon (? *namadicus*)				....	
Mammuthus (*Archidiskodon*) *Planifrons*	....	....			
Elephas (*Hypselephas*) *hysudricus*		....			
Elephas (*Platelephas*) *platycephalus*	....	....			
Elephas namadicus				....	

SPECIES AND THEIR GEOLOGICAL RANGES

Species	Upper pliocene	Pleistocene			
	Tatrot	Pinjaur	1st to 3rd Glacial	3rd Inter-glacial	4th Glacial
RHINOCEROTIDAE—					
Rhinoceros sivalensis		....			
Rhinoceros karnuliensis					....
Punjabitherium platyrhinum		....			
Rhinoceros deccanensis				....	
EQUIDAE—					
Equus sivalensis		....			
Equus namadicus				....	
Equus asinus					....
HIPPOPOTAMIDAE—					
Hexaprotodon sivalensis	....	....			
Hexaprotodon palaeindicus				....	
SUIDAE—					
Sus hysudricus	....	....			
Sus (? *namadicus*)				....	
CAMELIDAE—					
Camelus sivalensis	....	....			
GIRAFFIDAE—					
Sivatherium giganteum	....	....			
BOVIDAE—					
Sivacobus palaeindicus	....	....			
Hemibos triquetricornis	....	....			
Hemibos acuticornis	....	....			
Leptobos falconeri	....	....			
Pre-bison dehmi	....				
Bison sivalensis	....	....			
Bos namadicus				....	
Bubalus platyceros		....			
Bubalus palaeindicus				....	

age. The mammalian faunas that existed in India from the first to third glaciation are unknown so far, and the faunas of the last glaciation is poorly known. Until this knowledge is complete, actual geological ranges for the Pleistocene mammalian faunas of India will remain undefined. However, taking into account the origin, migration evolution, distribution and geological ranges of the various Pleistocene mammalian faunas of the world, the geological ranges of the Indian Pleistocene mammalian faunas can be inferred with a greater degree of precision by experienced palaeontologists. The geological ranges of the Indian mammalian faunas of the Pleistocene are given in the table.

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CATION EXCHANGE EQUILIBRIA

II. Na-Ca-Mg System of Soils and Clay Minerals

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Studies on cation exchange equilibria on two clay minerals (bentonite and kaolinite) and five soils of Rajasthan, using a wide range of salt concentration and SAR, were conducted. Ion exchange equations of Kerr, Vanselow, Krishnamoorthy and Overstreet, Gapon and that based on Donnan equilibria were compared for their suitability. It was observed that selectivity coefficient decreased with the increase of SAR. Gapon equation was found slightly better but on reducing the equations to the same form, the degree of deviation in the selectivity coefficient was nearly the same. Per cent deviation was more in soils than clay minerals. Some of the factors responsible for it are discussed.

Introduction

Various ion exchange equations have been proposed in literature (Kerr 1928, Vanselow 1932, Gapon 1933, Krishnamoorthy and Overstreet 1950, Bolt 1955) but comparative data on their suitability in systems involving Na-Ca and Mg are limited (Bower 1962, Paliwal 1961, 1966, 1967). Recently, Paliwal and Maliwal (1970) compared some cation exchange equations in Na-Ca systems of clay minerals and soils using varying salt concentration and SAR. It would, therefore, be of great use if extent of ion exchange processes could be evaluated in order to control and predict from the chemical composition for the equilibrium solution and selectivity coefficient of a suitable equation. The present paper deals with the cation exchange equilibria involving Na-Ca-Mg system of soils and clay minerals assuming that these are the main cations taking active part in the cation exchange processes under saline-sodic conditions. Attempt has also been made to compare some of the main ion exchange equations for their suitability under wide ranges of total salt concentration and SAR.

Experimental Procedure

Two clay minerals, kaolinite and bentonite, and five representative soils of Rajasthan, varying widely in their physico-chemical characteristics as described earlier (Paliwal and Maliwal 1970), were used in this investigation. The soils were brought in equilibrium by repeated leaching on the buchner funnel. The process was continued till the soil showed the same composition as the equilibrating solution. Excess salt was washed off with ethyl alcohol. The calculation of SAR and activity coefficient of the ions and estimation of exchangeable cations were done as reported earlier. Comparison of the equations of Kerr, Vanselow, Gapon, Krishnamoorthy, Overstreet and Donnan was made on the basis of least deviation from the mean value.

Results and Discussion

The data on the adsorption of sodium on soils and clay minerals reveal that it increases with the increase of salinity and SAR but the increase is not strictly in proportion to their relative increase in salinity and SAR (Tables I and II). Between the clay minerals, the degree of sodium saturation is more in kaolinite while the total sodium adsorption is more in bentonite on account of its higher cation exchange capacity. In case of soils also the total amount

Table I

Effect of salinity and SAR on the adsorption of cations by clay minerals

Solution No.	Composition of solution		Exchangeable cations (me/100 g)					
	Salinity (me/l)	SAR	Na	Ca	Mg	Na	Ca	Mg
				Bentonite			*Kaolinite*	
1	2·5	5·35	0·05	57·95	14·45	1·40	6·30	1·55
2	,,	10·57	8·95	54·85	13·65	2·60	5·45	1·28
3	,,	26·50	16·05	49·10	12·20	5·10	3·45	0·85
4	,,	53·40	25·00	42·00	10·50	6·20	2·35	0·50
5	,,	73·56	32·50	36·00	9·00	7·20	1·65	0·50
6	7·5	5·49	6·05	57·00	14·20	1·60	6·20	1·55
7	,,	11·05	10·75	53·45	13·25	3·00	5·10	1·25
8	,,	27·92	18·45	47·20	11·80	5·40	3·85	0·80
9	,,	55·23	29·00	38·40	10·10	6·40	2·30	0·50
10	,,	118·70	37·00	32·00	8·25	7·40	1·60	0·40
11	22·5	6·02	7·15	56·20	14·00	1·90	6·05	1·50
12	,,	11·96	13·05	51·50	12·80	3·30	4·95	1·20
13	,,	29·71	20·50	45·50	11·35	5·70	3·00	0·70
14	,,	59·68	32·85	36·00	8·60	6·95	2·00	0·40
15	,,	119·65	40·50	29·20	7·80	7·85	1·20	0·25
16	67·5	6·85	7·60	55·90	13·95	1·95	5·90	1·45
17	,,	13·78	14·45	50·40	12·55	3·30	4·85	1·20
18	,,	34·10	22·50	44·00	11·00	6·85	2·80	0·65
19	,,	68·20	38·45	30·20	8·75	7·50	1·55	0·35
20	,,	135·90	50·05	20·90	5·20	8·15	0·90	0·20

TABLE II

Effect of salinity and SAR on the adsorption of cations by soils

Solution No.	Exchangeable cations (me/100 g)														
	Na	Ca	Mg	Na	Ca	Mg	Na	Ca	Mg	Na	Ca	Mg	Na	Ca	Mg
	(*Kota*, *CEC* = 29·5)			(*Fatehnagar*, *CEC* = 23·5)			(*Pali*, *CEC* = 18·3)			(*Jodhpur*, *CEC* = 9·7)			(*Durgapura*, *CEC* = 8·1)		
1	3·00	21·20	5·30	2·70	16·64	4·16	2·20	15·80	3·95	1·40	6·64	1·66	1·30	5·44	1·36
2	3·40	20·88	5·22	2·95	16·44	4·11	2·40	14·88	3·72	1·50	6·56	1·53	1·50	5·28	1·32
3	3·70	20·64	5·16	3·05	16·36	4·09	2·60	14·72	3·68	1·75	6·36	1·59	1·85	5·00	1·25
4	4·50	20·00	5·00	3·35	16·12	4·03	3·60	11·52	2·88	2·25	5·96	1·49	2·20	4·72	1·18
5	5·60	19·12	4·78	3·50	16·00	4·00	4·00	11·20	2·80	2·60	5·68	1·42	2·40	4·56	1·14
6	3·90	20·48	5·12	4·20	15·44	3·86	2·75	12·20	3·05	2·20	6·00	1·50	1·50	5·28	1·32
7	4·14	20·28	5·07	4·30	15·36	3·84	3·50	11·60	2·90	2·65	5·64	1·41	2·00	4·88	1·22
8	4·60	19·92	4·98	4·70	15·04	3·76	4·20	11·04	2·76	3·20	5·20	1·30	2·50	4·48	1·12
9	5·00	19·60	4·90	4·95	14·84	3·71	4·55	10·76	2·69	3·50	4·96	1·24	2·80	4·24	1·06
10	5·45	19·24	4·81	5·20	14·64	3·66	4·60	10·72	2·68	3·75	4·76	1·19	3·00	4·08	1·02
11	4·60	19·92	4·98	3·75	15·80	3·95	2·80	12·16	3·04	2·35	5·24	1·31	2·20	4·72	1·18
12	5·45	19·24	4·81	5·10	14·72	3·68	4·50	10·80	2·70	2·80	5·12	1·28	2·60	4·40	1·10
13	6·30	18·56	4·64	6·50	13·60	3·40	5·50	10·00	2·50	3·75	4·76	1·19	2·70	4·32	1·08
14	7·75	17·40	4·35	7·50	12·80	3·20	5·70	9·84	2·46	4·40	4·24	1·06	3·20	3·92	0·98
15	8·50	16·80	4·20	7·50	12·80	3·20	5·90	9·68	2·42	4·70	4·00	1·00	3·50	3·68	0·92
16	5·50	19·20	4·80	4·50	15·20	3·80	4·20	11·04	2·76	3·00	5·36	1·34	2·30	4·64	1·16
17	6·40	18·48	4·62	5·50	14·40	3·60	4·50	10·80	2·70	3·20	5·20	1·30	2·50	4·48	1·12
18	7·55	17·48	4·37	6·50	13·60	3·40	6·10	9·52	2·38	4·80	3·92	0·98	3·50	3·68	0·92
19	9·65	15·88	3·97	9·55	11·16	2·79	8·35	7·72	1·93	5·80	3·12	0·78	4·45	2·92	0·73
20	12·15	13·88	3·47	10·75	10·20	2·55	9·00	7·20	1·80	6·10	2·88	0·72	4·80	2·64	0·66

of exchangeable sodium is more in soils having higher cations exchange capacity. This relative order can be expressed as Kota > Fatehnagar > Pali > Jodhpur > Durgapura. The adsorption of Ca to Mg ratio on the clay phase is nearly the same as that used in the equilibrium solution.

The adsorption of sodium in all these soils was more at all levels of salinity as compared to those of Na-Ca systems of these soils under identical conditions as reported earlier (Paliwal and Maliwal 1970). This indicates that though the soils were equilibrated with one and the same sodium concentration in both the systems, the adsorption of sodium was more when magnesium was included in place of calcium. It seems to be related with the lower chemical affinity of magnesium than calcium to the clay surface. Consequently, adsorption of sodium increases at the cost of magnesium. These observations support the views of Singh and Ramamoorthy (1965) and Chaddah (1970) who pointed out that chemical affinity of calcium and magnesium is not the same in spite of the fact that both are divalent and thus adsorption of sodium will not be the same in spite of the same value of SAR if there is significant variation in the proportion of calcium and magnesium.

The selectivity coefficient obtained by various ion exchange equations for clay minerals and soils decreases with the increase of SAR irrespective of the type of equation used but the relative change varied with the type of exchange material and the equation used. At a particular SAR, the effect of salinity was such that the selectivity coefficient generally increased with the

TABLE III

Coefficient of variation (%) in selectivity coefficient calculated from different ion exchange equations

Salinity levels (me/1)	Kerr	Vanselow	Krishnamoorthy and Overstreet	Gapon	Donnan
			Bentonite		
2·5	43·4	57·5	48·0	13·6	25·0
7·5	50·0	62·5	59·0	22·4	26·1
22·5	56·5	67·3	57·8	20·3	29·8
67·5	40·7	55·3	50·0	10·2	22·5
All salinity	52·3	65·9	60·0	22·7	25·1
			Kaolinite		
2·5	27·1	38·7	29·3	17·2	12·5
7·5	48·5	55·5	51·3	11·4	27·1
22·5	38·0	49·4	43·9	8·7	25·3
67·5	48·2	40·5	36·6	16·2	18·6
All salinity	41·2	49·1	42·1	19·3	21·8

TABLE IV

Coefficient of variation (%) in selectivity coefficient calculated from different ion exchange equations

Salinity levels (me/1)	Kerr	Vanselow	Krishna-moorthy and Overstreet	Gapon	Donnan
Kota					
2·5	131·9	128·8	116·8	71·8	78·0
7·5	138·2	137·3	135·7	86·3	74·7
22·5	126·4	128·0	126·5	72·5	76·6
67·5	124·1	109·6	125·5	70·3	72·3
Total	141·3	132·8	138·8	68·8	77·5
Fatehnagar					
2·5	133·3	133·8	133·2	77·5	68·0
7·5	140·4	140·6	140·5	88·9	90·3
22·5	109·6	126·4	112·1	63·9	67·4
67·5	116·6	119·4	117·7	63·9	67·9
Total	132·0	137·6	132·4	77·5	67·9
Pali					
2·5	128·0	125·4	125·8	61·7	73·7
7·5	118·2	123·2	121·3	72·2	73·4
22·5	99·9	103·9	99·4	61·3	68·5
67·5	117·0	122·5	124·2	63·9	72·9
Total	139·5	140·7	138·8	73·5	84·5
Jodhpur					
2·5	129·8	132·9	131·9	70·9	70·7
7·5	113·9	121·7	120·3	70·4	75·3
22·5	128·2	125·9	127·0	66·0	70·1
67·5	119·0	118·3	120·0	55·9	65·9
Total	128·5	140·0	139·2	73·8	78·0
Durgapura					
2·5	121·2	122·7	122·2	64·6	71·2
7·5	109·7	165·2	116·9	65·7	70·8
22·5	127·4	128·4	129·8	75·1	77·5
67·5	120·1	123·9	121·7	58·4	67·7
Total	137·4	146·7	137·9	72·4	75·3

increase of salt concentration for all the soils and clay minerals irrespective of the equation used. In general, the form of ion exchange equations is such that the selectivity coefficient is more for exchange complex of low cation exchange capacity than those of higher CEC.

The coefficient of variation calculated from the selectivity coefficient data is generally more for soils than clay minerals where surface properties are more uniform. Of the equations compared, the coefficient of variation was more for the equations of Kerr, Vanselow, Krishnamoorthy and Overstreet than Gapon and that based on Donnan equilibria (Tables III and IV). In spite of a very large deviation in selectivity coefficient, Gapon's equations showed the least variation followed by Donnan and the rest showed much higher deviation by a factor of 1·5 to 2·0 that of Gapon's equation.

The above results clearly indicate that Gapon and Donnan type equations show much less deviation under very wide limits of salinity and SAR and can be concluded as more suitable for explaining the distribution of ions between soils and solution phases. A perusal of the expressions used reveals that the ion exchange equations of Kerr, Vanselow and Krishnamoorthy and Overstreet are of mass action type with an additional factor in the denominator for the exchangeable cations and the forms of Gapon and Donnan are nearly the square root of the other equations used.

In order to examine how far the deviation is caused by the nature of the ion exchange equation, the selectivity coefficients were recalculated by taking the square root of the selectivity coefficient obtained by the equations of Kerr, Vanselow, Krishnamoorthy and Overstreet for the soils where the deviation was much more. It was observed (Table V) that per cent deviation had significantly reduced and had come at par with those obtained by the equations of Gapon and Donnan in all the soils at all levels of salt concentration either combined together or separately. These results suggest that the wide variations for mass action type equations are mainly due to their forms and on reducing them to the same type the variation is not of much significance. However the Gapon equation is still slightly superior, which seems to be related to its form which is nearly the square root of other mass action type equations in addition to its theoretical formulation. In spite of this the degree of variation is so much that it is hardly of any use for quantitative prediction value, for exchangeable sodium status of the soil. Such a high degree of deviation in the selectivity coefficient even under equilibrium conditions seems due to the non-uniformity of surface charge density of soils, variation in the activity coefficient of the exchangeable cation with its degree of saturation, and presence of mixture of different types of exchange material in the soils.

It may, therefore, be concluded that on reducing the equations of Kerr, Vanselow, Krishnamoorthy and Overstreet to similar form of Gapon and Donnan, there is no significant difference between themselves.

TABLE V

Coefficient of variation (%) in selectivity coefficient after taking their square roots

Salinity levels (me/l)	$K^{\frac{1}{2}}_{\text{Kerr}}$	$K^{\frac{1}{2}}_{\text{V}}$	$K^{\frac{1}{2}}_{\text{K\&O}}$	K_{G}
		Kota		
2·5	77·4	74·5	71·1	71·8
7·5	90·5	86·2	86·0	86·3
22·5	76·6	76·3	75·6	72·5
67·5	72·7	73·2	72·2	70·3
Total	88·2	80·2	78·8	68·8
		Fatehnagar		
2·5	61·3	82·1	80·8	77·5
7·5	88·8	88·5	88·1	88·8
22·5	70·2	75·6	67·5	63·9
67·5	66·6	68·5	65·2	63·9
Total	75·8	81·8	77·2	77·5
		Pali		
2·5	75·9	69·2	68·8	61·7
7·5	75·5	76·3	76·9	72·2
22·5	65·5	67·1	64·0	61·3
67·5	71·1	70·7	68·8	63·9
Total	77·3	80·0	75·4	73·5
		Jodhpur		
2·5	75·9	77·7	74·1	70·9
7·5	77·6	75·2	72·7	70·3
22·5	79·0	74·8	74·1	66·1
67·5	68·9	67·5	66·1	55·9
Total	81·2	78·2	74·2	73·8
		Durgapura		
2·5	70·6	74·1	71·2	64·7
7·5	72·8	70·4	72·4	65·7
22·5	83·3	80·0	80·3	75·1
67·5	88·8	72·3	67·2	58·4
Total	85·5	77·9	76·5	72·4

K = Constant; V = Vanselow; K and O = Krishnamoorthy and Overstreet; G = Gapon

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RANDOM SELF-AVOIDING LATTICE WALKS

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A general method to arrive at the approximate estimate of the number of distinct self-avoiding random lattice walk configurations of a given length is illustrated with the examples of some two-dimensional and three-dimensional regular lattices. The sequence of the numbers of distinct self-avoiding random walk configurations is shown to form an asymptotically geometrical progression. For one case, the estimates are compared with the correct values.

INTRODUCTION

A comprehensive theory is available for the problem of unrestricted random lattice walks in literature (Chandrasekhar 1943, Kac 1947, Wang and Uhlenbeck 1945). The analysis of unrestricted random lattice walks is relatively straightforward, because they belong to a class of Markovian random processes. Self-avoiding random lattice walks are of interest in the theory of co-operative phenomena in crystals (Domb 1960). They are also recognized as an appropriate model of a linear polymeric chain (Gans 1965). They are relevant in the analysis of some two-dimensional picture processing schemes based on figure extraction and coding (Moharir and Prasada 1969). But almost no analytical information is available regarding self-avoiding random lattice walks, the reason being that they belong to a class of non-Markovian random processes.

The properties of random self-avoiding lattice walks are generally studied by exact enumeration approach (Domb 1960) and Monte Carlo methods (Wall *et al.* 1954, Hammersley and Mortan 1954). Exact enumeration can be carried out only for small walk-lengths and then recourse must be taken to extrapolation for longer walk-lengths. Monte Carlo method generates a representative sample of walks of given length and assumes that the properties determined for this sample are valid in a statistical sense for all the walks of given length. Improvements over normal Monte Carlo methods have been devised (Gans 1965, Wall and Erpenbeck 1959). But both these approaches are time-consuming and use extrapolation and generalization which may not be valid. An approximate estimate of the number of distinct self-avoiding random walk configurations of a given length has been obtained in this paper for two-dimensional rhombic lattice, two-dimensional square lattice and three-dimensional cubic lattice. But the method used is general in scope and can be used for any other lattice, e.g. three-dimensional tetrahedral lattice.

On a two-dimensional rhombic lattice every sample point is defined to have six 'neighbours' $n_1, n_2, \ldots, n_6$ as shown in Fig. 1(*a*).

On a two-dimensional square lattice every sample point is defined to have four 'neighbours' n_1, n_2, n_3 and n_4 as shown in Fig. 1(*b*).

On a three-dimensional cubic lattice every sample point is defined to have six 'neighbours' $n_1, n_2, \ldots, n_6$ as shown in Fig. 1(*c*).

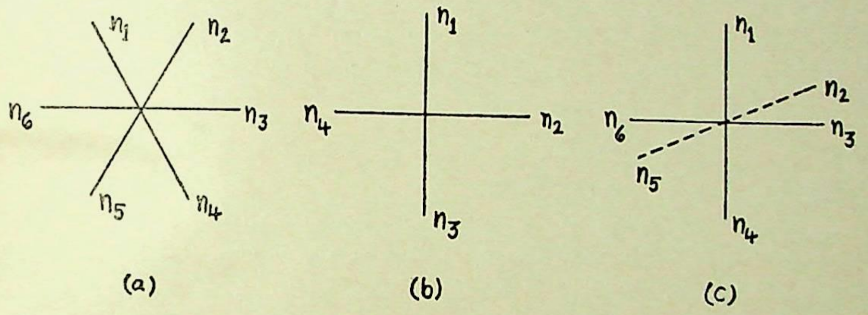

FIG. 1. Neighbours of a sample point on (*a*) a two-dimensional rhombic lattice, (*b*) a two-dimensional square lattice and (*c*) a three-dimensional cubic lattice.

A sample point may be joined by a 'line' only to one (or more) of its neighbours.

A 'walk' is a sequence beginning with a point and ending with a point in which points and lines alternate.

The 'length' of a 'walk' is the number of lines in it.

A 'path' or a 'self-avoiding walk' is a walk in which all sample points are distinct.

TWO-DIMENSIONAL RHOMBIC LATTICE

It can be assumed that the walk begins from the origin. The first line, i.e. the second point, can be chosen in w_1 ways where

$$w_1 = 6. \quad \ldots \quad (1)$$

The second line, i.e. the third point, can now be chosen in w_2 ways where

$$w_2 = 5 \quad \ldots \quad (2)$$

because the walk cannot be retraced.

Now onwards care must be taken that mth point $(m \geqslant 4)$ is not on the walk already. The rth point would be $(m-r-1)$ lines away from the $(m-1)$th point. Thus rth point has to be within a hexagon of sides of $(m-r)$ points as shown in Fig. 2 with $(m-1)$th point at the centre. There are z_r points in this hexagon where

$$\begin{aligned} z_r &= 2[(m-r)+(m-r+1)+\ldots+(2m-2r-3)+(2m-2r-2)] \\ &\qquad +(2m-2r-1) \\ &= (m-r-1)(3m-3r-2)+(2m-2r-1). \qquad \ldots \quad (3) \end{aligned}$$

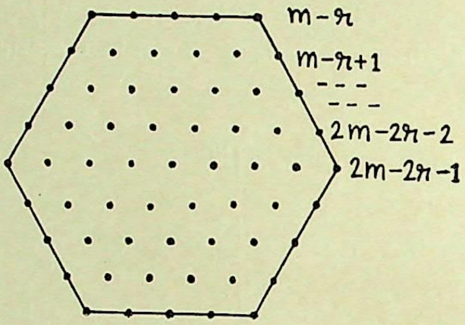

FIG. 2. A region of the sampling lattice spanned by $(m-r-1)$ lines on a two-dimensional rhombic lattice.

Of these $(r+1)$th, $(r+2)$th, ..., $(m-2)$th and $(m-1)$th points, i.e. in all $(m-r-1)$ points must be excluded because every point on the walk is assumed to be distinct. Thus rth point is one of the t_r points where

$$t_r = z_r-(m-r-1) = 3(m-r-1)^2+(2m-2r-1). \qquad \ldots \quad (4)$$

That is, the prospective mth point on the self-avoiding random walk could have been the rth point on the walk already with the probability $1/t_r$. That is, the prospective mth point could already have been on the walk with the probability p_m where

$$\begin{aligned} p_m &= \sum_{r=1}^{m-3} 1/t_r = \sum_{r=1}^{m-3} \frac{1}{3(m-r-1)^2+(2m-2r-1)} \\ &= \sum_{r=3}^{m-1} \frac{1}{2(r-1)^2+(2r-1)}. \qquad \ldots \quad (5) \end{aligned}$$

Thus mth point or $(m-1)$th line on an average can be chosen in w_{m-1} ways where

$$w_{m-1} = 5[1-p_m] = 5\left[1-\sum_{r=3}^{m-1} \frac{1}{3(r-1)^2+(2r-1)}\right], \quad m \geqslant 4. \qquad \ldots \quad (6)$$

The number $q(n)$ of distinct self-avoiding random walk configurations of length n is then given by

$$q(n) = \tfrac{1}{2}w_1 \cdot w_2 \ldots w_{n-1} \cdot w_n. \qquad \ldots \quad (7)$$

The factor $\frac{1}{2}$ appears because self-avoiding random lattice walk has two open ends and every walk has therefore been counted twice in the above procedure. From eqn. (7) it follows that

$$\frac{q(n)}{q(n-1)} = \frac{w_1 \,.\, w_2 \ldots w_{n-1} \,.\, w_n/2}{w_1 \,.\, w_2 \ldots w_{n-1}/2} = w_n \quad \ldots \quad \ldots \quad \ldots \quad (8)$$

where from eqn. (6) we have

$$w_n = 5\left[1 - \sum_{r=3}^{n} \frac{1}{3(r-1)^2+(2r-1)}\right],\ n \geqslant 3. \quad \ldots \quad \ldots \quad (9)$$

w_n has been tabulated for a rhombic lattice in Table I. From Table I and eqn. (8), it follows that $q(n)$ forms an asymptotically geometrical progression as n increases.

TABLE I

nth line in a self-avoiding random walk can be chosen on an average in w_n ways on a two-dimensional rhombic lattice

n	w_n	n	w_n
1	6	16	4·2340
2	5	20	4·2125
3	4·7060	24	4·1985
4	4·5590	28	4·1885
5	4·4715	32	4·1810
6	4·4135	36	4·1750
7	4·3720	40	4·1705
8	4·3410	44	4·1665
9	4·3170	48	4·1630
10	4·2980	52	4·1610
11	4·2825	56	4·1590
12	4·2695	60	4·1570
		64	4·1550

TWO-DIMENSIONAL SQUARE LATTICE

Using the same notation as in above section, we have

$$w_1 = 4 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (10)$$

$$w_2 = 3 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (11)$$

$$w_3 = 3. \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (12)$$

So far we have 4 points on the walk. Now onwards care must be taken that mth point ($m \geqslant 5$) is not on the walk already. The rth point would be

$(m-r-1)$ lines away from the $(m-1)$th point. Thus the rth point has to be within a square shown in Fig. 3. The square contains z_r points where

$$
\begin{aligned}
z_r &= 2[1+3+5+\ldots+(2m-2r-3)]+(2m-2r-1) \\
&= 2(m-r-1)^2+(2m-2r-1). \qquad \ldots \quad (13)
\end{aligned}
$$

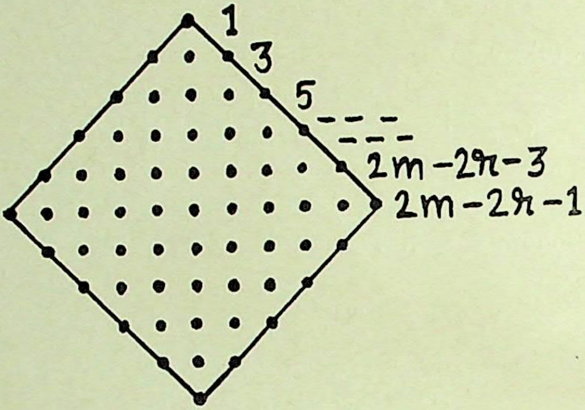

Fig. 3. A region of the sampling lattice spanned by $(m-r-1)$ lines on a two-dimensional square lattice.

But $(r+1)$th, $(r+2)$th, ..., $(m-2)$th and $(m-1)$th points must be excluded because every point on the walk is assumed to be distinct. Thus rth point is one of the t_r points where

$$t_r = 2(m-r-1)^2+(m-r). \qquad \ldots \quad (14)$$

So the prospective mth point on the walk could have been the rth point already with probability $1/t_r$. Note that m and r must be either both even or both odd. This follows easily because for the mth point on the walk to be the rth point already, $(m-r)$ lines must form a cyclic walk. This can happen on the two-dimensional square lattice only if $(m-r)$ is an even number. Thus the prospective mth point could already have been on the walk with the probability

$$p_m = \sum_{r=1,3,5,\ldots}^{m-4} 1/t_r = \sum_{r=1,3,5,\ldots}^{m-4} \frac{1}{2(m-r-1)^2+(m-r)}\,; \; m \text{ odd}, m \geqslant 5 \qquad (15)$$

and

$$p_m = \sum_{r=2,4,6,\ldots}^{m-4} 1/t_r = \sum_{r=2,4,6,\ldots}^{m-4} \frac{1}{2(m-r-1)^2+(m-r)}\,; \; m \text{ even}, m > 5. \qquad (16)$$

Thus mth point or $(m-1)$th line on an average can be chosen in w_{m-1} ways where

$$w_{m-1} = 3(1-p_m); \; m > 5 \qquad \ldots \quad (17)$$

where p_m is given by eqns. (15) and (16).

Eqns. (7) and (8) are valid for this section also.

w_n has been tabulated for a square lattice in Table II. From Table II and eqns. (8), (15), (16) and (17), it follows that $q(n)$ forms an asymptotically geometrical progression as n increases.

TABLE II

nth line in a self-avoiding random walk can be chosen on an average in w_n ways on a two-dimensional square lattice

n	w_n	n	w_n
1	4	26–27	2·7201
2–3	3	30–31	2·7162
4–5	2·8635	34–35	2·7132
6–7	2·8098	38–39	2·7108
8–9	2·7816	42–43	2·7090
10–11	2·7642	46–47	2·7075
12–13	2·7525	50–51	2·7063
14–15	2·7441	54–55	2·7051
18–19	2·7327	58–59	2·7039
22–23	2·7252		

THREE-DIMENSIONAL CUBIC LATTICE

Using the same notation as in previous section, we have

$$w_1 = 6 \qquad \ldots \quad (18)$$

$$w_2 = 5 \qquad \ldots \quad (19)$$

$$w_3 = 5. \qquad \ldots \quad (20)$$

So far we have 4 points on the walk. Now onwards care must be taken that the mth point ($m \geqslant 5$) is not on the walk already. The rth point on the walk would be $(m-r-1)$ lines away from the $(m-1)$th point. The rth point has to be within a diamond shown in Fig. 4 with $(m-1)$th point at the centre. It may be noted that $OA = OB = OC = OD = OE = OF = (m-r-1)$ lines and that every cross-section of the diamond perpendicular to AF (or BD or CE) is a square similar to one in Fig. 3. Therefore, the diamond contains z_r points where

$$\begin{aligned} z_r &= 2\sum_{t=1}^{m-r-1}[2(t-1)t+1]+[2(m-r-1)(m-r)+1] \\ &= \tfrac{2}{3}(m-r-1)(m-r)(2m-2r-1)+(2m-2r-1). \qquad \ldots \quad (21) \end{aligned}$$

But $(r+1)$th, $(r+2)$th, . . . , $(m-2)$th and $(m-1)$th points must be excluded, because every point on the walk is assumed to be distinct. Thus rth point is one of the t_r points where

$$t_r = \tfrac{2}{3}(m-r-1)(m-r)(2m-2r-1)+(m-r). \qquad \ldots \quad (22)$$

Thus the prospective mth point on the walk could have been the rth point already with probability $1/t_r$. Note that m and r must be either both even or both odd. Thus the prospective mth point could already have been on the walk with probability p_m where

$$p_m = \sum_{r=1,3,5,\ldots}^{m-4} \frac{1}{\frac{2}{3}(m-r-1)(m-r)(2m-2r-1)+(m-r)}; \; m \text{ odd}, \; m \geqslant 5 \qquad (23)$$

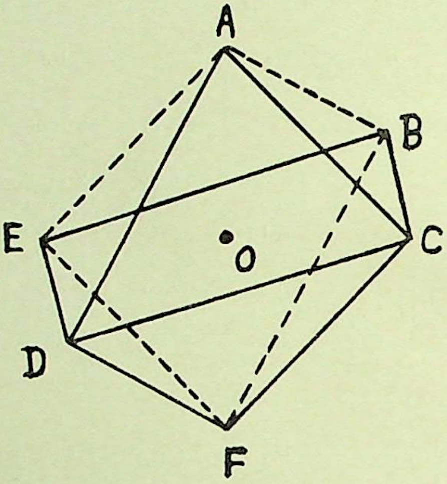

FIG. 4. A region of the sampling lattice spanned by $(m-r-1)$ lines on a three-dimensional cubic lattice.

and

$$p_m = \sum_{r=2,4,6,\ldots}^{m-4} \frac{1}{\frac{2}{3}(m-r-1)(m-r)(2m-2r-1)+(m-r)}; \; m \text{ even}, \; m > 5. \qquad (24)$$

Thus mth point or $(m-1)$th line, on an average, can be chosen in w_{m-1} ways where

$$w_{m-1} = 5(1-p_m); \; m \geqslant 5 \quad \ldots \quad \ldots \quad \ldots \quad \ldots \; (25)$$

where p_m is given by eqns. (23) and (24). Eqns. (7) and (8) are valid for this section also. w_n has been tabulated for a cubic lattice as a function of n in Table III. From Table III and eqns. (8), (23), (24) and (25) it follows that $q(n)$ forms an asymptotically geometrical progression as n increases. Number of distinct self-avoiding random walk configurations on a cubic lattice were obtained by exact enumeration by Domb for small walk lengths. His values of w_n are compared with the estimates of this paper in Table IV. From Table IV it follows that the estimates of w_n of this paper are higher than the correct value. Therefore, estimates of $q(n)$ also would be higher than the correct value. Moreover, as the product of w_m's is to be used to obtain the estimate of $q(n)$, as n increases the error in the estimate of $q(n)$ would grow.

TABLE III

nth line in a self-avoiding random walk can be chosen on an average in w_n ways on a three-dimensional cubic lattice

n	w_n	n	w_n
1	6	18–19	4·87575
2–3	5	20–21	4·87525
4–5	4·91665	22–23	4·87485
6–7	4·89455	24–25	4·87455
8–9	4·88575	26–27	4·87430
10–11	4·88140	28–29	4·87410
12–13	4·87895	30–31	4·87395
14–15	4·87745	32–33	4·87385
16–17	4·87645		

TABLE IV

Comparison of our estimates of w_n with the exact values for three-dimensional cubic lattice

n	Domb's exact value of w_n	Estimated w_n of this paper	Error %
2	5·000	5·000	0
3	5·000	5·000	0
4	4·840	4·917	1·6
5	4·868	4·917	1·0
6	4·789	4·895	2·2
7	4·809	4·895	1·7
8	4·767	4·886	2·4
9	4·779	4·886	2·2

It may be noted that the disparity between the estimates and the correct value of w_n monotonously increases for both odd and even values of n. It may be conjectured from the close look at Table IV that this disparity would reach a constant value asymptotically as n grows. The conjecture may of course prove wrong.

Similar disparity may exist between the estimates and the correct values of w_n for the other lattices. The disparity can be reduced by using refined models. In the evaluation of z_r for the two-dimensional rhombic lattice, two-dimensional square lattice and three-dimensional cubic lattice, hexagon, square and diamond respectively of the maximum axial extension equal to $2(m-r-1)$ lines have been used. Better estimates would be obtained by using average maximum axial extension, the average being taken over various self-avoiding walks. This average would obviously be less than $2(m-r-1)$. Thus a lesser value of z_r, correspondingly a larger value of p_m and hence a lesser value of w_{m-1} would be obtained. The results could be further improved by using probability distribution over the axial extension for a given self-avoiding walk length. No analytical methods are available to obtain the average maximum axial extension or the probability distribution over the axial extension. Data regarding average maximum axial extension and mean-square end-to-end extension for the self-avoiding random walks based on Monte Carlo methods are available only for tetrahedral lattice (Gans 1965). For the two-dimensional square lattice data based on Monte Carlo methods for mean-square end-to-end extension alone are available (Wall and Erpenbeck 1959).

CONCLUSION

An approximate estimate of the number of distinct self-avoiding random walk configurations of a given length is obtained for two-dimensional rhombic lattice, two-dimensional square lattice and three-dimensional cubic lattice. The method used, however, is general in scope and can be used for any other lattice. This follows from the fact that the problem reduces to the count of lattice points contained in a volume (or area) that can be spanned by the lattice walks of given length. This count is straightforward for most lattices. In case of the cubic lattice the estimates are compared with the correct values available in the literature and it is found that the estimates are consistently higher. The analysis shows that the sequence of the numbers of distinct self-avoiding random walk configurations forms an asymptotically geometrical progression.

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JADUGUDA—CERTAIN OBSERVATIONS REGARDING URANIUM AND BASE METALS MINERALIZATION*

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Active prospecting and mining for uranium has been in progress in Jaduguda mines.
The zone of economic uranium mineralization is about 1,000 metres long and has been prospected up to a depth of 425 metres.
Details regarding the structural controls of uranium and base metals mineralization in the Jaduguda deposit have been outlined. The spatial relationship between uranium and the base metals are also discussed in the light of geophysical and geochemical (soil) surveys. The probable sequence of tectonic and metasomatic activity in Jaduguda has been discussed.

INTRODUCTION

Jaduguda (lat. 22° 39′: long. 86° 20′) uranium deposit is located almost in the centre of the Singhbhum copper belt (Dunn 1937) in Bihar. The deposit was discovered in 1951 when the entire copper belt was closely examined for the occurrence of radioactive minerals. Active prospecting and mining have been in progress there since then, and a fair amount of details regarding the nature and extent of the radioactive mineralization in the deposit has been gathered. Nickel and molybdenum occur in association with uranium in contained parts of the uranium ore-shoots. The paper briefly outlines the spatial relationship between the base metals and uranium in the deposit.

GEOLOGICAL SETTING

The rock types seen in the Jaduguda hill (Fig. 1) from north to south are (1) garnetiferous muscovite schist, (2) quartzite (cherty), (3) muscovite kyanite quartz schist, (4) mylonite, (5) quartz breccia, (6) conglomerate (autoclastic), (7) granular rock (biotite-chlorite-apatite-magnetite-ilmenite, tourmaline, uraninite quartz rock), (8) chlorite-biotite quartz rock, (9) talc-chlorite schists, (10) coarse-grained quartzite and (11) epidiorite.

The foliation strike of the rocks is NW-SE and the dip is to the NE.

The most important structural feature of the copper belt, in which Jaduguda is situated, is the zone of thrusting and shearing along which mineralization has taken place.

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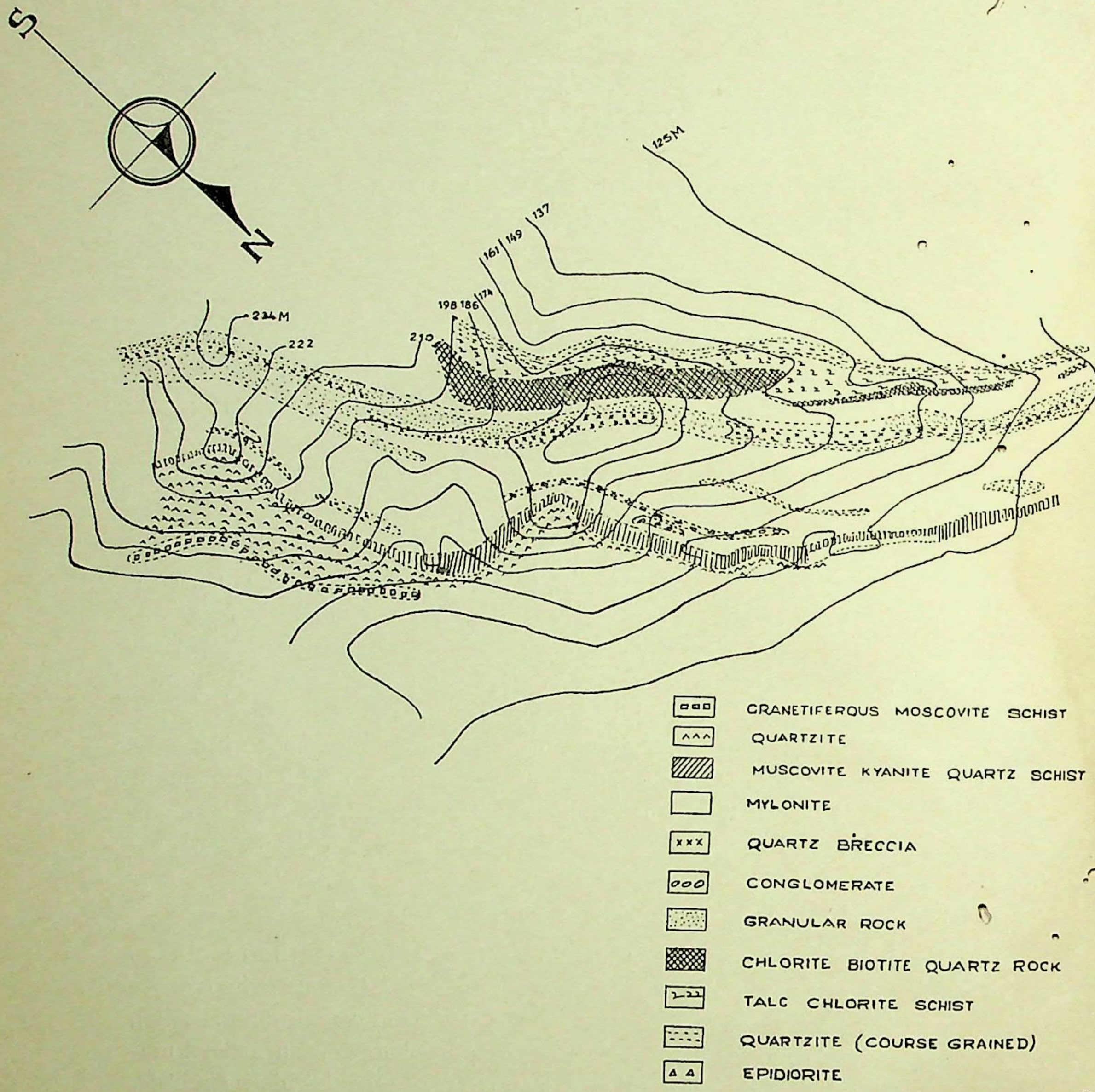

FIG. 1. Geological map of Jaduguda mines (scale : 1 : 5,000).

RADIOACTIVE ORE BODIES AND THEIR CONTROL

There are two radioactive lodes in Jaduguda separated by a pile of rocks 60 metres in thickness (Fig. 2). The southern lode known as the foot-wall lode spreads over a strike length of 1,000 metres from east to west. This lode is not uniform either in the distribution or concentration of the ore elements, which is expressed in the development of two ore shoots known as the eastern

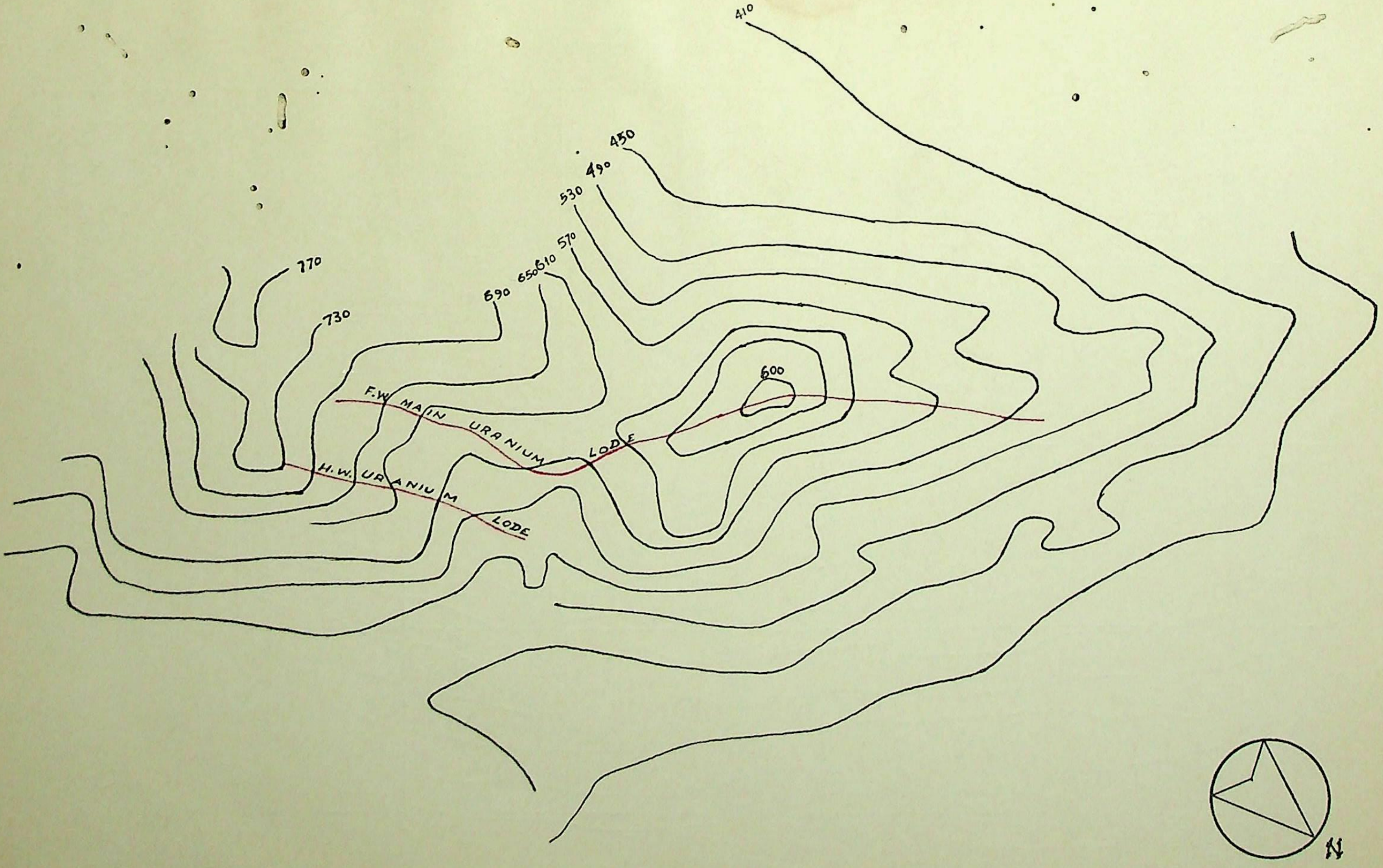

FIG. 2. Contour map of Jaduguda hill showing the uranium lodes (scale : 1 : 5000).

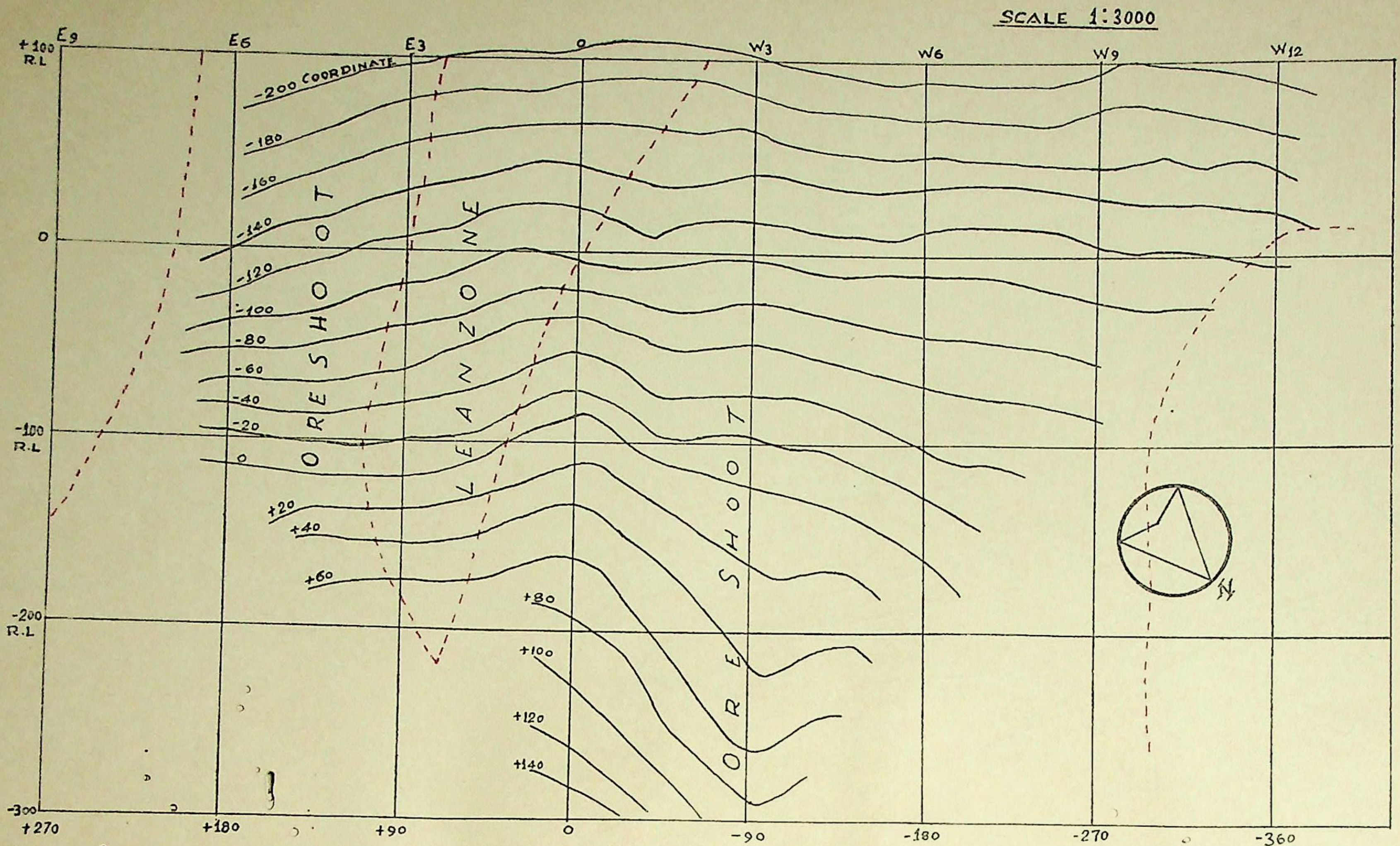

FIG. 3. Vertical longitudinal section of the stratum contours showing the cross-folding (F. W. Lode).

Jaduguda lode and central Jaduguda. The northern lode or the hang-wall lode is traceable only in the east for a strike length of 200 metres. Of these, the central Jaduguda ore shoot in the foot-wall lode is most interesting, not only because it is the largest and richest but also because it contains nickel and molybdenum in addition to uranium.

The ore shoots plunge almost down dip parallel to the predominant linear structures in the area, usually represented by elongated minerals, mineral aggregates, pucker in schist-ore rocks, stretched and stressed pebbles. Folds of different dimensions (the larger ores being generally open) also occur in the down dip direction (Fig. 3). This direction varies from NE to ENE.

The predominant planar structures in the area are the bedding (obliterated but now reckoned from the interfaces of the sedimentogenic rock units), schistosity and shear planes which may be respectively called S_1, S_2 and S_3 for convenience of reference. It is interesting to note that all the three S planes are parallel to one another. The ore bodies occur parallel with them. Since all the above three planes are mutually parallel or sub-parallel it is difficult to assert with certainty with which one the lodes exactly coincide. But in view of the fact that the ore bodies and crushed zones are closely related in space, it may be reasonably concluded that the shearing which produced the crushed zones and shear planes (the two varying only the scale) had an important part to play in localizing the ore bodies. Further it has been observed in the underground mine workings that the ore bodies cut through S_1 and S_2 planes.

Regarding the down dip folds, cross-folds (Fig. 3) which occur in all the three S planes enumerated above, it is suggested that, after the deposition of the uranium, the shear zone was subjected to compression across its length, accompanied by lateral shear, and as a result the hang-wall side relatively moved westwards. Along such new shear planes deposition of molybdenite took place. This is borne out by the lateral shortening of the ore body at Jaduguda where it is more closely folded, and the cutting through of the uranium lode by the molybdenite-bearing shears (the strike-slip shears) (Fig. 8), the shift of the sliced uranium ore body and the striations on the mineralized and unmineralized shear surfaces.

LITHOLOGICAL FEATURES

The radioactive mineralization in Jaduguda is mainly structurally controlled, the mineralization being confined to the shears which are parallel or sub-parallel to the foliation of the rocks, the first order structural control earlier mentioned. Nevertheless certain rock types are not mineralized even though they are sheared and brecciated.

The rock type which are mineralized are: (1) the biotite-chlorite-schists, (2) chlorite-biotite-quartz-apatite-magnetite-ilmenite-tourmaline rock (termed the granular quartz rock in the mine), (3) the tectonic conglomerates and (4) brecciated quartzites.

Rock types which are invariably barren are: (*a*) the mylonites, (*b*) the basic rocks like the basic sills and (*c*) the epidiorites. Even though the mylonites are sheared and crushed, they are never mineralized but they grade into mineralized brecciated quartzites along their strike.

All rock types which are mineralized show schistocity when examined as thin sections under the microscope. Even the so-called granular quartz rock, which is composed of chlorite-biotite-quartz-tourmaline-apatite-ilmenite-magnetite and uraninite, is seen to be a schist under the microscope. The granular rock may be best described as a siliceous schist with varying amounts of biotite chlorite, tourmaline apatite, etc. The quartzites show clear brecciation with square angular pieces of quartz.

Auto-radiographs of the mineralized rock types show that uranium occurs as disseminations of uraninite and not as veins and veinlets. Some of the biotite of the biotite schists also show pleochroic halos. The biotite and chlorite schists abundant in the upper levels become relatively scarcer in the deeper levels and the brecciated quartzite and granular rocks become the predominating rock types at depth. Magnetite, seen in such abundance in the granular rock in the upper levels, gives place to haematite at depth. A little feldspar (oligoclase ?) is also seen, especially in the granular rock. Secondary silica is found in minor amounts in the quartzites.

Gradewise, the best mineralized rock types are the brecciated quartzites, with granular rock as a close second. The schists are the poorest in grade.

It may be mentioned here that there are also zones of granular rock and tectonic conglomerates in the mine, which are barren of uranium mineralization. This adds to the belief that the mineralization in Jaduguda is controlled by structures rather than by lithology.

The mylonites may be described as quartz schist with subordinate amounts of biotite and chlorite. These rock types occur invariably close to and along the shears.

The basic rock types even when they are sheared are not mineralized. This is in conformity with the theoretical considerations that generally rule out basic rocks as favourable hosts for uranium mineralization.

BASE METALS IN THE URANIUM ORES OF JADUGUDA

Chemical analyses of the uranium ore from central Jaduguda indicated an appreciable content of base metals, primarily nickel and molybdenum. The following ore minerals have been identified in the uranium ores (Sarkar 1966):

Magnetite ($FeOFe_2O_3$), ilmenite ($FeOTiO_2$), martite (Fe_2O_3), uraninite (UO_2+x), rutile (TiO_2), chalcopyrite ($CuFeS_2$), pyrrhotite (Fe_x–IS_x), marcasite

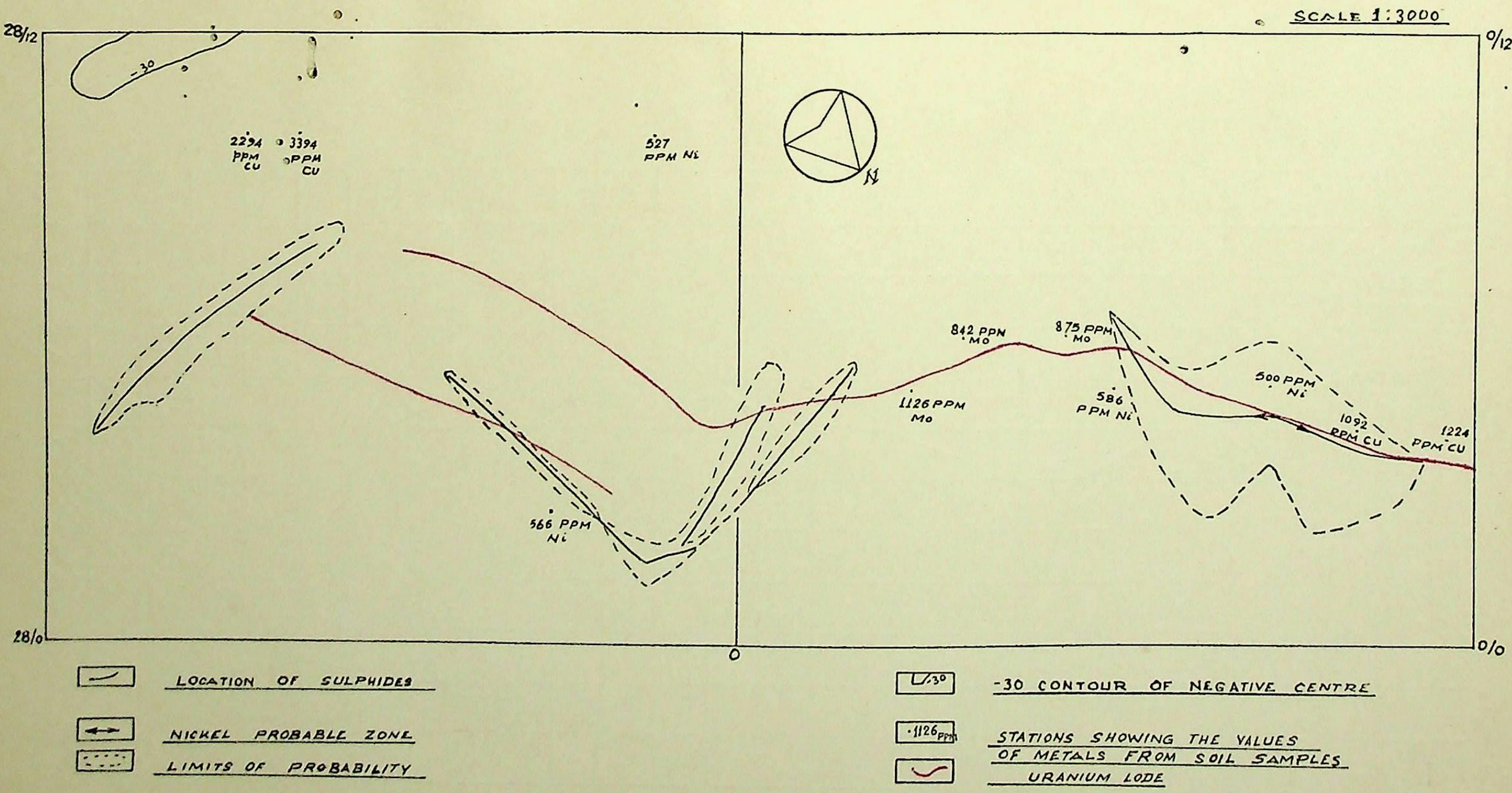

Fig. 4. Map showing the distribution of combined sulphide with the uranium lodes projected on the surface and also showing metal peaks.

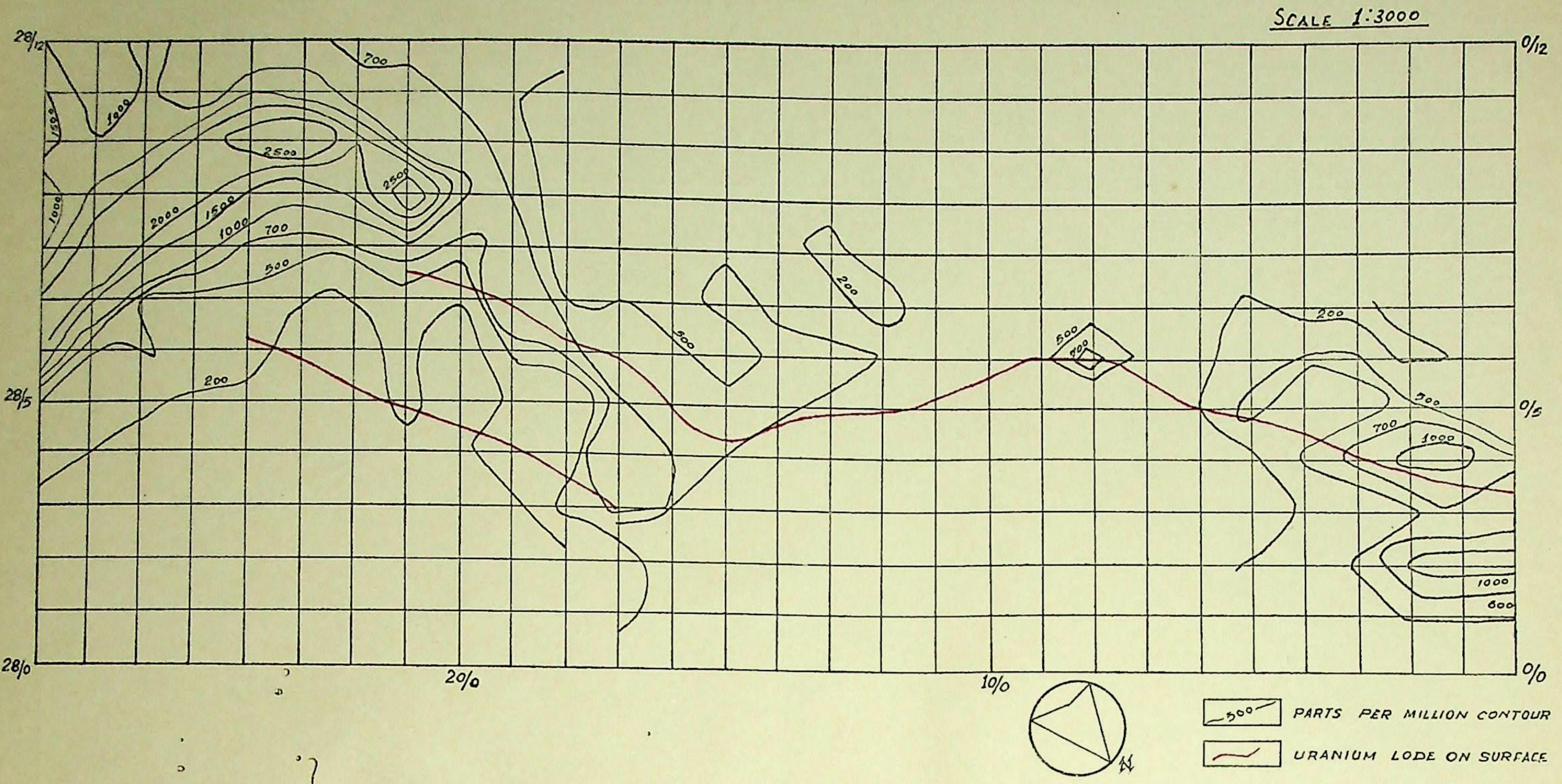

FIG. 5. Copper dispersion pattern at Jaduguda.

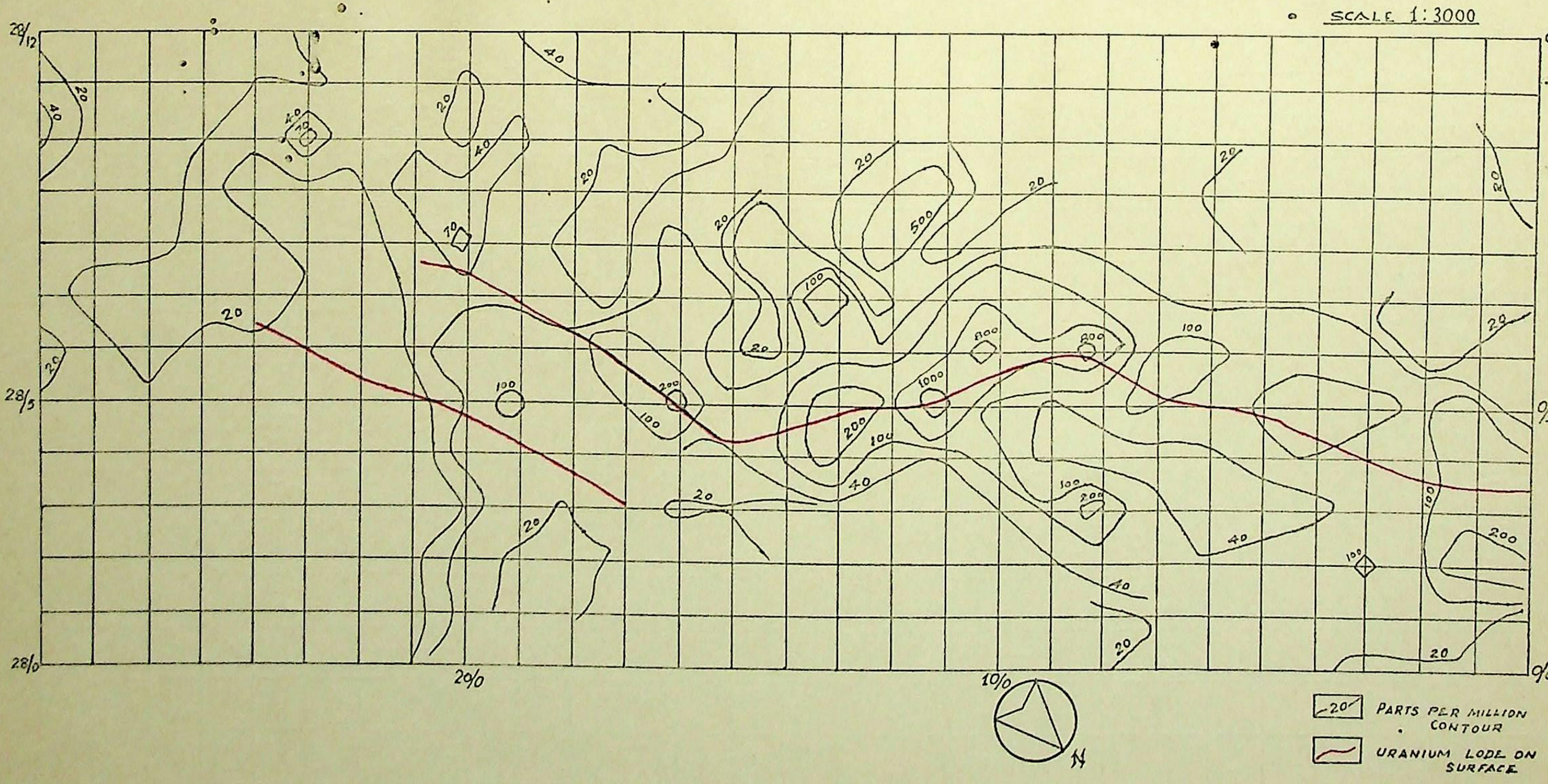

FIG. 6. Molybdenum dispersion pattern at Jaduguda.

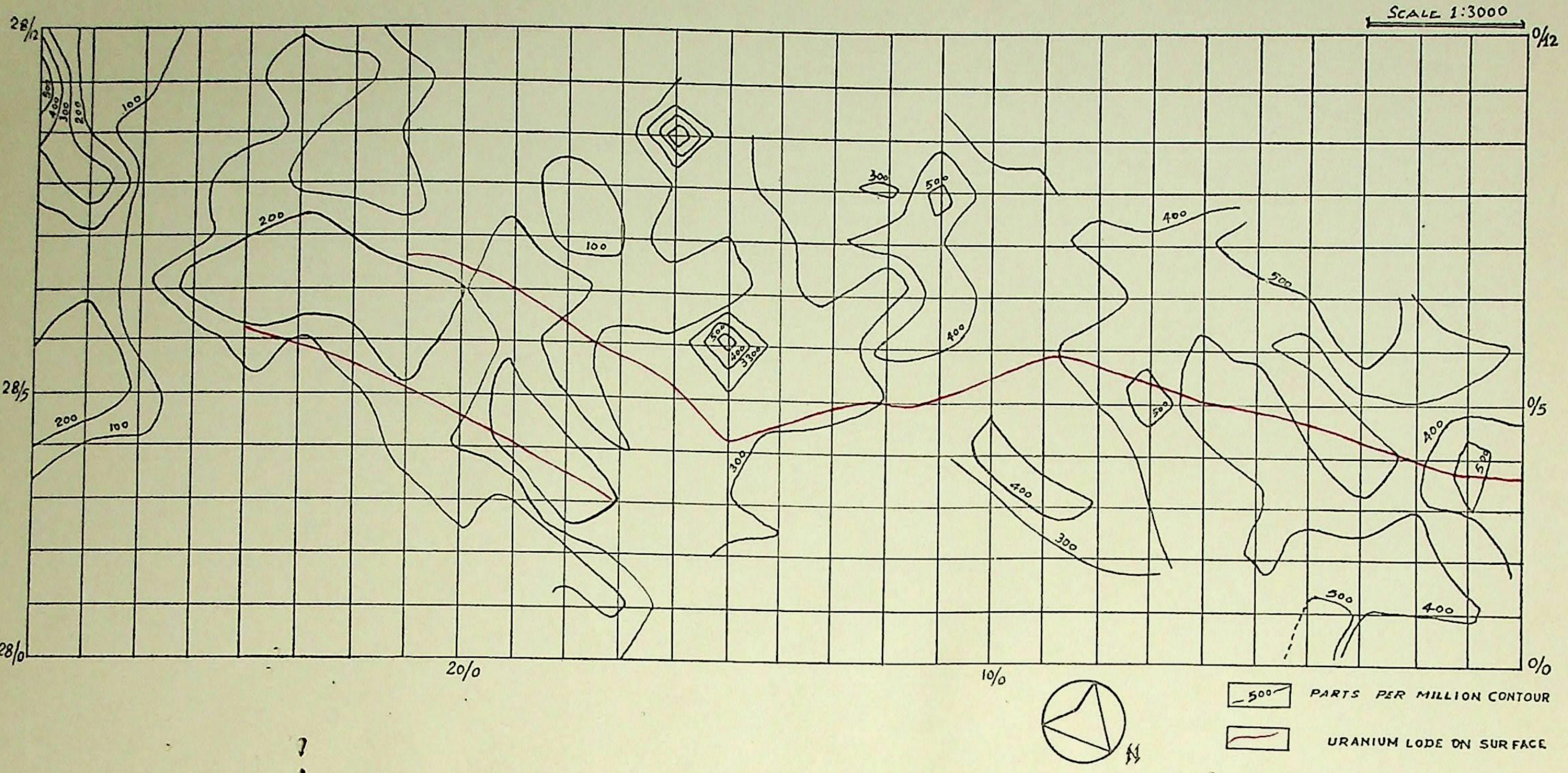

FIG. 7. Nickel dispersion pattern at Jaduguda.

(FeS_2), pyrite (FeS_2), mackinawite (FeS), pentlandite ($FeNiS$), violanite ($FiFeS_4$), tellurbismuth (Bi_2Te_3), tetradyrite (Bi_2Te_2S), cubanite ($CuFe_2S_3$) and molybdenite (MoS_2).

GEOPHYSICAL AND GEOCHEMICAL (SOIL) SURVEY IN JADUGUDA

In order to demarcate the sulphide lodes, if any, in Jaduguda, and to know their position in space in the deposit *vis-à-vis* the uranium lodes, geophysical (self-potential and magnetic) (Murthy and Bhatnagar 1967) and geochemical (soil) (for Cu, Ni and Mo) surveys were carried out.

The geophysical anamolies and the distribution of the peak values of different metals are shown in Fig. 4. It will be seen from the geophysical anamolies that the magnetic sulphide ore bodies (probably nickeliferous) are mostly in the western and the central parts of the deposit, while the non-magnetic sulphide ore bodies are in the SE part of the deposit. These findings corroborate fairly well with the data obtained from the mine.

SPATIAL RELATIONSHIP BETWEEN URANIUM AND THE BASE METALS

It will be seen from the dispersion of the base metals (Fig. 4) on the surface of the deposit that the position of the individual base metals *vis-à-vis* uranium can be made out fairly clearly:

(1) Copper with its distinct dispersion pattern is to the south-east of the uranium lode (Fig. 5).

(2) Molybdenum is found to be associated with the uranium lode and extends a little to the south of it (Fig. 6).

(3) Nickel is found in greater abundance in the central, the western and the south-western parts of the hill than in the eastern part (Fig. 7). There is comparatively a greater abundance of the metals in the south-western part of the hill than on the eastern side.

STRUCTURES ASSOCIATED WITH BASE METALS MINERALIZATION

The most important structures associated with the base metals mineralization,. particularly molybdenum, are the strike-slip shears observed in central Jaduguda. The strike-slip shears have not only thickened certain portions of the main uranium lode but have also been mineralized with molybdenite. A prominent strike-slip shear about 6″ wide, completely mineralized with molybdenite, seen on the surface level in the mine, can be followed down dip to the deeper levels (Fig. 8).

Copper is found to the south of the uranium lode, particularly on the eastern side. It is probable that in Jaduguda the copper sulphides which were subsequent to uranium in the paragenetic scheme (Sarkar 1966, Bhattacharya *et al.* 1966) mineralized the later formed shear to the south of the uranium lodes.

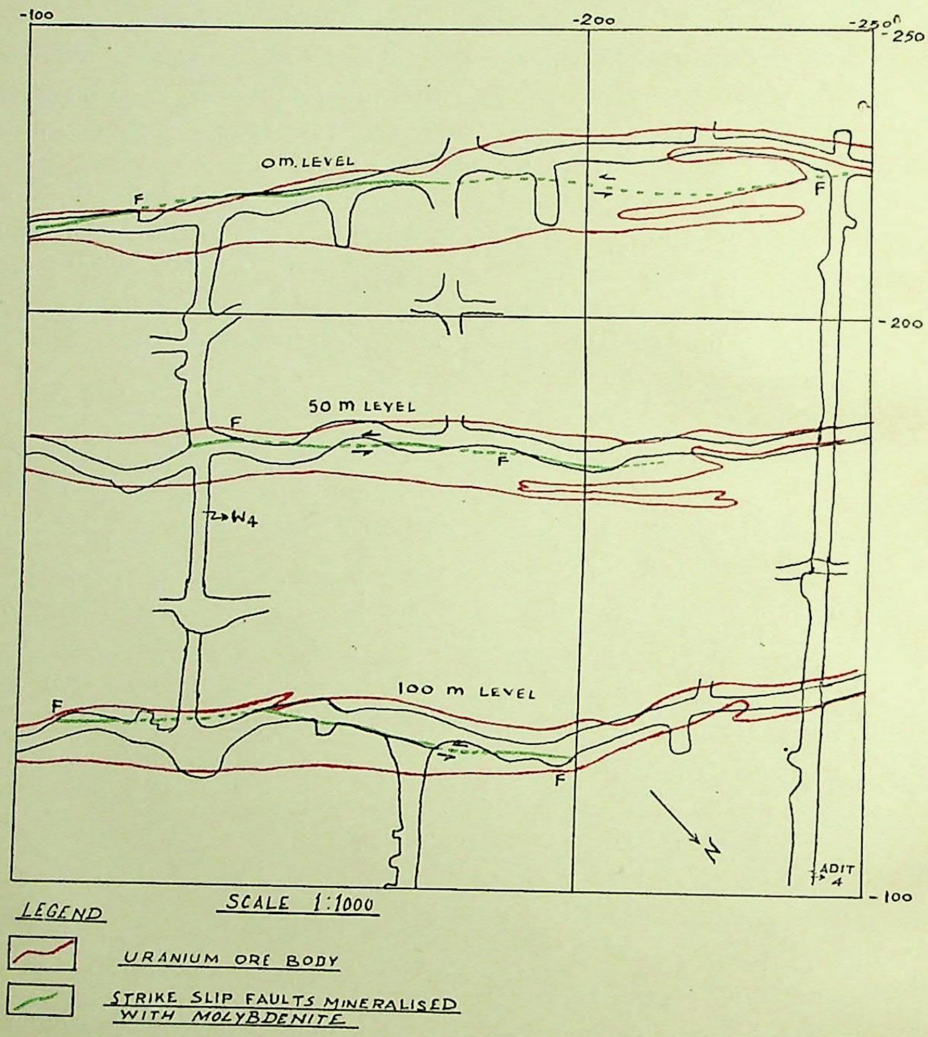

FIG. 8. Plan showing thickened uranium ore body and strike-slip faults mineralized with molybdenite.

Nickel is found in comparatively greater amounts in the central Jaduguda ore shoot and persists down to the depth to which the uranium lodes have been prospected. It is quite possible that the earlier formed shears mineralized with uraninite were reopened during the rejuvenation of tectonic activity, and the sulphides like pyrite and pyrrhotite mineralized the reopened shears.

TECTONIC ACTIVITY AND MINERALIZATION IN JADUGUDA

From the data available so far, the following suggestions are offered tentatively regarding the tectonic activity and mineralization in Jaduguda:

(1) To begin with, the rocks constituting the lodes in Jaduguda may be considered as derived from essentially siliceous sediments. These sediments were thrust, folded and sheared by forces acting from the north-east (the slicken side direction). The thrusting formed the principal fold and the axial plane shears trending NW–SE in Jaduguda. The sediments were metamorphosed into quartz schist and quartzite. The autoclastic conglomerates were probably formed during this period.

(2) The tectonic activity abated in intensity after the formation of the principal fold and the axial plane shears and the metasomatic activity set in. During this period of metasomatic activity, apatite, magnetite, ilmenite, uraninite, tourmaline were introduced into the shears in the quartz schists and quartzites, along with biotite and chlorite.

(3) At the end of the apatite-magnetite-uraninite-tourmaline-metasomatism there was a rejuvenation of the tectonic activity, resulting in new shears to the south of the earlier formed mineralized shears. Some of the early formed mineralized shears were also reopened. Down-dip folds (cross-folds) were formed during this period due to lateral compression. Strike-slip faults were a consequence of this lateral compression. Differential movements resulted in the formation of the mylonites. The tectonic activity probably once again abated in intensity after this second period of deformation.

(4) At the close of the rejuvenated activity or closely following it, the second phase of metasomatism, namely that of the sulphides, set in. The earlier sulphides like pyrite, pyrrhotite, pentlandite, molybdenite, etc., mineralized the reopened mineralized (uranium) shears and the strike-slip shears, with the result that nickel and molybdenum are found in greater abundance in the thickened portion of the uranium lode in central Jaduguda than elsewhere. The last of the sulphides, namely that of copper (chalcopyrite), mineralized the later formed shears to the south of the uranium lodes. The end of this second phase of metasomatic activity marked the end of mineralization in Jaduguda.

(5) The last tectonic episode in Jaduguda area was the development of the Turukocha fault, which has transversely cut across most of the rock units in the area as well as the mineralized zone, laterally shifting it by about 1 km. This is thought to be a post-mineralization fault as it is totally barren of any mineralization.

ACKNOWLEDGEMENT

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ATOMIC MINERAL DEPOSITS IN BIHAR MICA BELT*

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The geology of the Bihar Mica Belt has been discussed in the paper with special reference to controls for emplacement of pegmatites, their distribution, genesis and behaviour both laterally and in depth. It also describes the occurrences of minerals required for atomic energy, like beryl, lithium minerals, columbite-tantalite, etc., in the pegmatites of this belt, which occupies the premier position in the country not only for mica, but also in respect of production and potentialities of these minerals. The possibilities of additional discoveries of deposits of beryllium, columbium and tantalum, etc., by geochemical prospecting and by exploration for large low-grade deposits of the same are also discussed.

It is concluded that this rich and promising belt will continue to play an important role in India's industrial development by meeting the country's requirement of atomic minerals occurring in pegmatites.

I. INTRODUCTION

Of the three mica belts in India, the Bihar Mica Belt is the most important from the point of view of production and superior quality of its mica which accounts for earning valuable foreign exchange to the tune of Rs.12 to 13 crores per annum. Besides, it occupies a premier position in respect of output and reserves of various atomic minerals, viz. beryl, lepidolite, columbite-tantalite, refractory uranium ore-minerals, etc., which occur as important accessories and are obtained largely as by-product during mica mining.

It is appropriate at this stage to briefly review our knowledge of this important belt, to which substantial contributions have been made as a result of efforts of the Atomic Minerals Division of the Department of Atomic Energy for almost two decades.

In this paper the distribution of the above-cited important atomic minerals in pegmatites, their geological occurrences and genesis and other pertinent features such as the future outlook and ways and means to be adopted for quick appraisal of these minerals are discussed.

II. GEOLOGY OF BELT

The mica belt, covering parts of Gaya, Hazaribagh, Monghyr and Bhagalpur districts, extends almost east-west for 125 km and is about 55 km in its widest extent. The atomic minerals-bearing pegmatites occur in only about half of this total area of 7,000 sq km, the rest being covered by alluvium (Fig. 1).

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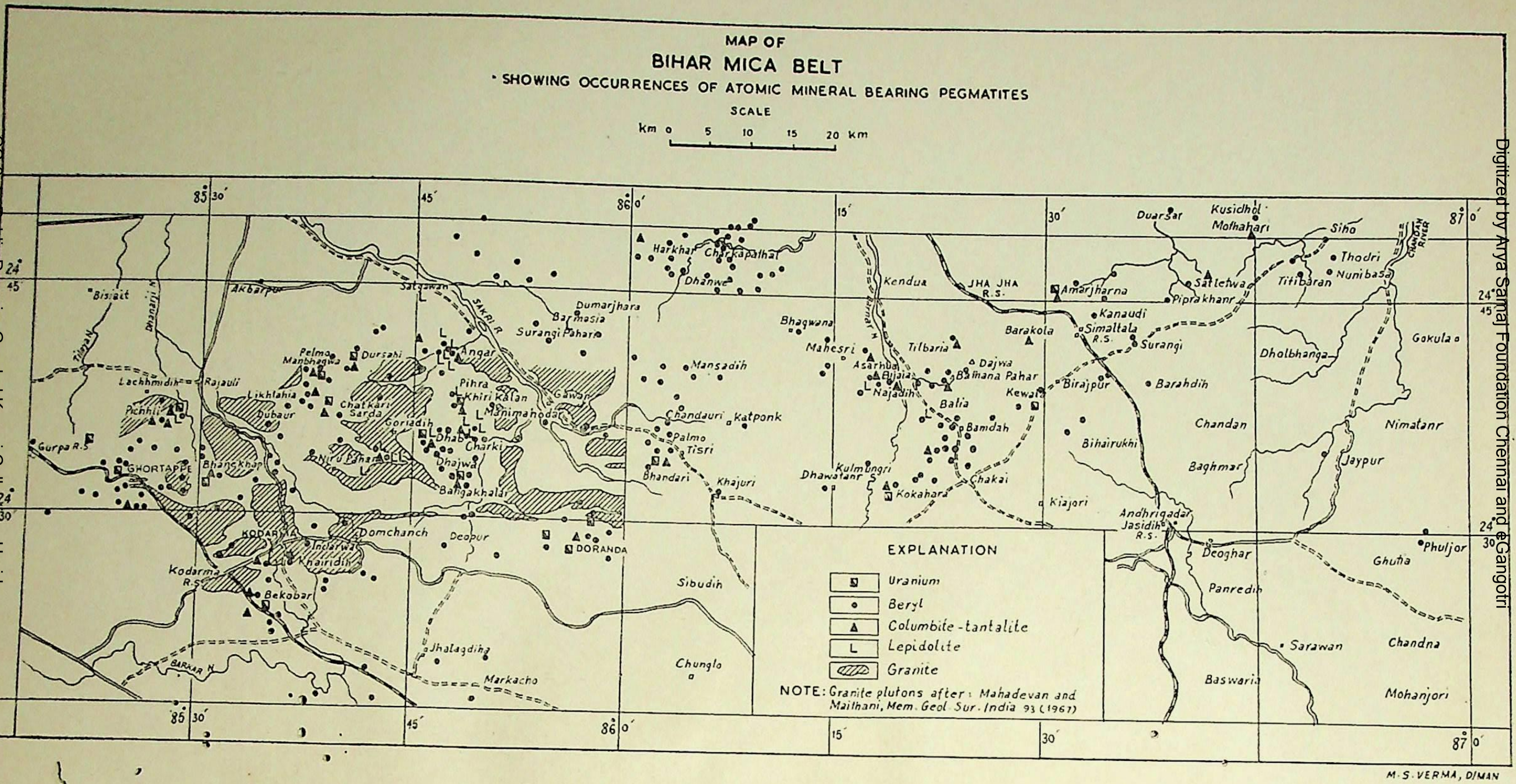


FIG. 1 Granite shown only in western part of belt.

The belt is covered by the meta-sedimentary rocks of Archaean Age comprising muscovite schist, biotite schist and muscovite-biotite schist carrying sillimanite (fibrolite), garnet and staurolite, with quartzite (generally micaceous), hornblende schist, calc-silicate granulite and hornblende gneiss. These rocks, which were deposited in a geosynclinal basin during the Dharwarian (Huronian) period, are well foliated and puckered and exhibit metamorphic grade of almandine-amphibolite facies.

These rocks have been extensively intruded by post-Dharwarian plutons of medium to coarse-grained, massive, leucocratic biotite granites of pink and light grey colour, containing subordinate hornblende and often large phenocrysts of pink feldspar. There are also intrusions of meta-dolerite, garnetiferous-ortho-amphibolites and actinolite-tremolite schists and of pegmatites.

Holland (1902) described this granite as the 'Dome Gneiss' as it forms prominent dome-shaped hills and is foliated near its contacts with the country rocks. Generally a hybrid feldspathised mica schist marks the contact of the country rocks and the granite, the bulk of which is however unfoliated, though xenoliths of country rocks, in varying degrees of transformation, have been observed in it.

III. STRUCTURE

Structurally, the Bihar Mica Belt appears to be a nearly east-west trending anticlinorium with several subsidiary folds, the outer flanks of which are formed by the quartzite standing out as high ridges, especially on the north.

The granite bosses have mostly intruded into the cores of the larger anticlines and have parental association with pegmatites which they resemble in composition.

IV. PEGMATITES

The pegmatites are emplaced along joints, tension fractures, foliation, bedding, shear planes, noses and limbs of folds, etc.; the massive pegmatitic intrusions appear to have been localized by cross-folding. They have generally concordant relation with the country rock, but are occasionally discordant to it also. They dip at all angles from almost flat to vertical, and in a few cases, e.g. at Doranda, steeply dipping veins send off almost horizontal offshoots along the foliation of the country rocks (Fig. 3).

It has been observed that the atomic minerals bearing pegmatites are generally localized close to the fringe of the granite plutons, where they display richer concentrations of these minerals, while commercial mica-bearing pegmatites occur in the schist away from them (Fig. 1).

The size and shape of pegmatites differ greatly, but generally they form long, narrow veins which thin out at either end and also at depth. Most of these lenticular veins pinch out and swell. The shapes of the pegmatites are indications of the structures that controlled their emplacement and physico-chemical conditions under which they were formed.

Detailed study in the field as well as systematic core drilling of a few pegmatites has shown that, as is generally the case laterally, in depth also the pegmatites are as a rule lenticular in shape, and consequently do not continue downward to a great depth, but sooner or later pinch out. Further, most of them have a tendency to pitch or plunge.

Besides quartz, microcline, albite and mica, the pegmatites of the Bihar Mica belt carry topaz, tourmaline, garnet, apatite monazite, and other phosphates, cassiterite, uraninite, beryl, columbite and tantalite, lithium minerals, rare earth minerals, etc.

The atomic minerals in commercial quantities occur only in 'zoned' or 'segregated' pegmatites. The zoning seems to be most pronounced in the middle portion of the lens where there is generally a well-developed quartz core, which may be single or branching, centrally situated or peripheral.

When followed in depth in a mine or by core drilling, the zoned pegmatites have been found to follow the scheme of textural behaviour (Vlasov 1952). Thus a well-developed quartz core at the surface may give place to detached lenses or it may totally disappear even at a shallow depth, and a block microcline zone may give place to an intergrowth zone of admixture of quartz and feldspar. Both the structure and texture of the pegmatite observed at the outcrop depend on the extent of erosion which it has undergone, hence it is possible that in the case of those pegmatites which are exposed at or below the middle portion, there would naturally be a tendency for the quartz core to gradually disappear in depth and for the feldspar to give place to intergrowth (or admixture) zone before the pegmatite totally fades out. This factor has an important bearing on the occurrence, distribution and chances of finding concentrations of economic minerals like, mica, beryl, lithium minerals, uranium minerals, columbite-tantalite, etc.

On the basis of age determination of uraninite of Singer, Gaya district, and lepidolite from Monghyr and monazite crystals from several localities, (Aswathanarayana 1964) it appears that the pegmatites of the Bihar Mica Belt were emplaced 955±50 m.y. ago, at the closing stage of the Satpura orogeny.

V. OCCURRENCES OF ATOMIC MINERALS

(i) *Beryl*

India is endowed with a large number of deposits of beryl in pegmatites, which have since the thirties yielded large quantities of mineral of commercial grade, the major part having been produced since the Atomic Minerals Division launched a vigorous drive for its production and procurement in 1949. In its beryl resources India occupies fourth or fifth place in the world after Brazil, Argentina, Mozambique and possibly South Africa.

The major part of Indian production has been contributed by about two dozen lessees of the Bihar Mica Belt, where the grade has practically always been over 10% of BeO, the highest being 13·5%. In the past, the mica mine owners evinced little interest in the exploitation of pegmatites containing atomic minerals in this area, as they did not contain good quality of commercial mica. The situation however changed considerably from mid-fifties onwards as a result of special vigorous efforts made by the Atomic Minerals Division.

In this belt, beryl has been found to occur in some 250 pegmatites, of which barely 50 can be classed as very good or outstanding in respect of their potentiality of beryl production. The proportion of pegmatites which can be worked exclusively for beryl on a commercial scale over some period is very limited and in most cases this mineral is obtained as a by-product of mica, quartz and feldspar mining and quarrying. Sometimes one portion of the mine is worked for mica and beryl is extracted from some other parts.

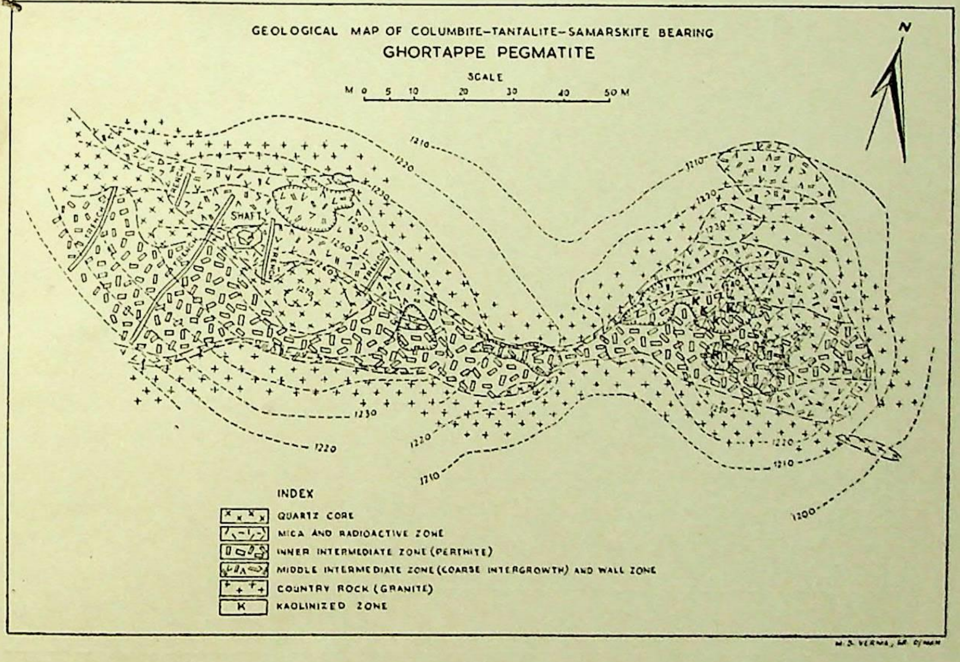


FIG. 2

A reference to the map of the Bihar Mica Belt (Fig. 1) will show that beryl-bearing pegmatites are unevenly distributed in the belt and they have a tendency to occur in clusters close to the borders of the granite batholiths. The deposits are concentrated in four areas, viz. the western, west-central, east-central and eastern, there being rather a large gap between the two last-mentioned areas. One solitary occurrence of chrysoberyl only of academic interest is reported from Ghortappe pegmatite (Fig. 2).

Like other atomic minerals, beryl occurs in commercial quantities only in the 'zoned' pegmatites, the large euhedral crystals occurring close to the quartz core at or near its junction with block microcline in association with large masses of green wedge-shaped (*jatai*) mica. Giant crystals of beryl have been observed at Bendi, Chatkari, Sarda (Fig. 5), and other localities. Small beryl crystals however occur in quartz-albite-microcline-perthite intergrowth forming the wall zone in association with albite or its cleavelandite variety. Here also the muscovite occurs as greenish flakes of poor quality; at Bhanakhap, good quality mica occurs in a separate zone in the same pegmatite containing beryl associated with green mica (Figs. 3–8).

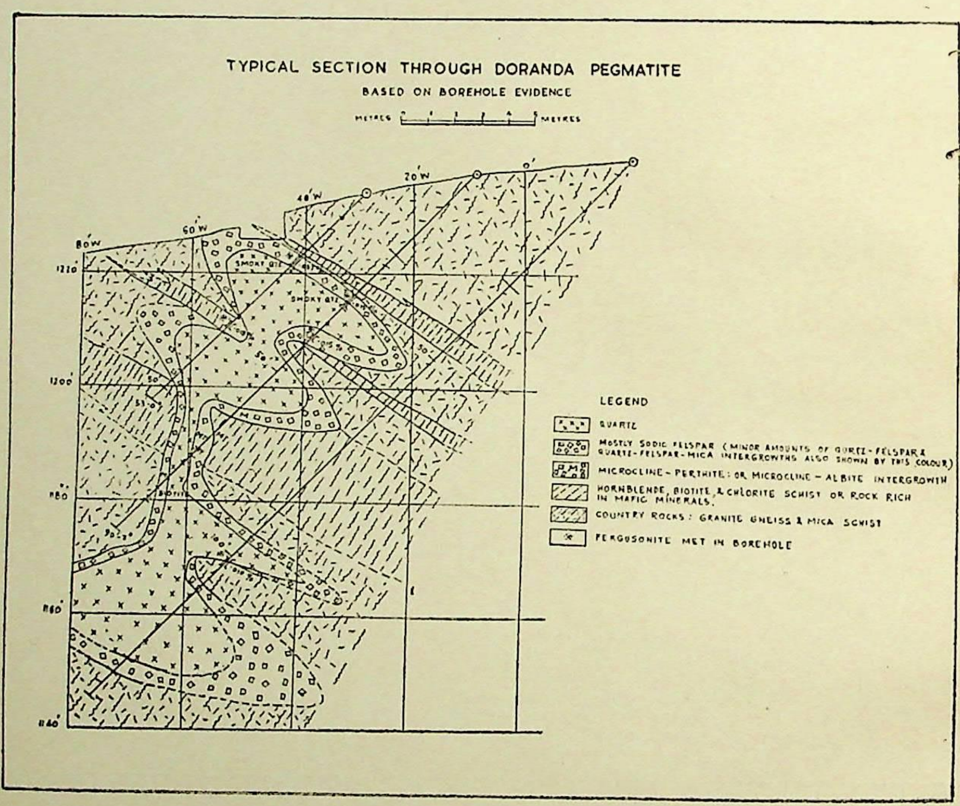

TYPICAL SECTION THROUGH DORANDA PEGMATITE
BASED ON BOREHOLE EVIDENCE
METRES 0 1 2 3 4 5 METRES
80'W
60'W
40'W
20'W
0'
1210'
1200'
1180'
1160'
1140'
SMOKY QTZ
SMOKY QTZ
BIOTITE
LEGEND
QUARTZ
MOSTLY SODIC FELSPAR (MINOR AMOUNTS OF QUARTZ-FELSPAR & QUARTZ-FELSPAR-MICA INTERGROWTHS ALSO SHOWN BY THIS COLOUR)
MICROCLINE-PERTHITE: OR MICROCLINE-ALBITE INTERGROWTH
HORNBLENDE, BIOTITE, & CHLORITE SCHIST OR ROCK RICH IN MAFIC MINERALS.
COUNTRY ROCKS: GRANITE GNEISS & MICA SCHIST
FERGUSONITE MET IN BOREHOLE

Fig. 3

Our observations are in agreement with those of Beus (1962) that, according to their physical and chemical properties, beryls can be classed into:

I. *Alkali-free beryls* (with total alkalies less than 0·5%) which are green, blue or yellow green in colour and occur as long prismatic crystals in unreplaced pegmatites; example Bhanakhap (Appendix III).

II. *Alkali beryls* (with total alkali content over 0·5%) which are of pale green, yellow, greenish-white or white colour and occurs as short prismatic crystals in replaced pegmatites (Fig. 10).

Alkali beryls are further subdivided into:

1. *Sodium beryl* ($Na_2O = 0{\cdot}5\%–2\%$; $Li_2O = 0{\cdot}1–0{\cdot}5\%$) yellow, greenish white or white in colour.
2. *Sodium-lithium beryl* ($Li_2O = 0{\cdot}5–1{\cdot}5\%$ $Na_2O = 1–2{\cdot}5\%$) greenish white, white or colourless.

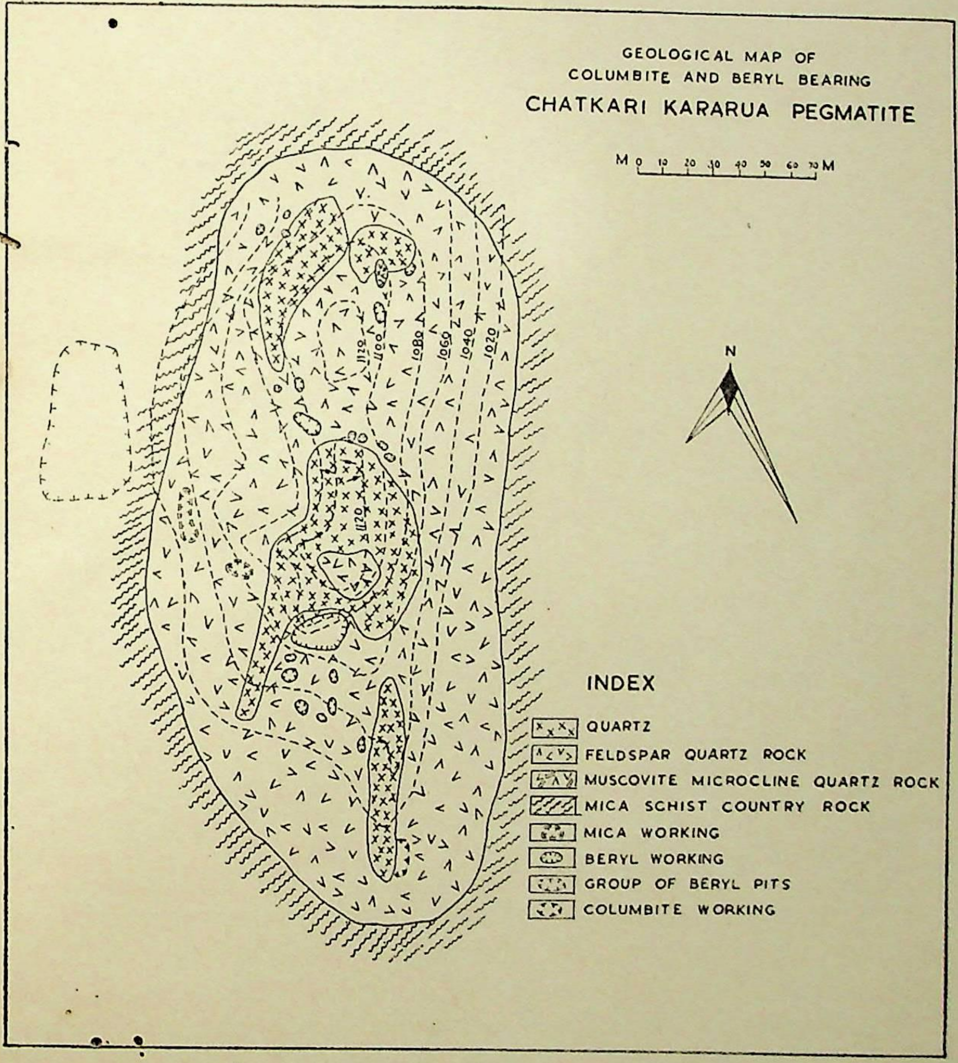


FIG. 4

Example: Asarhua a sample from where has been found to analyse $Na_2O = 0{\cdot}92\%$, $Li_2O = 0{\cdot}45\%$, $Cs_2O = 0{\cdot}26\%$ and $Rb_2O = 0{\cdot}01\%$.

3. *Lithium-Caesium beryl* ($Li_2O = 0{\cdot}1$–1%, Cs_2O up to 3% and Na_2O 0·3–1%) which is colourless, pinkish-white or rose-pink.
   Example: Barakola (Charki Surangi), a sample from where on analysis has given $Na_2O = 1{\cdot}68\%$, $Li_2O = 0{\cdot}91\%$, $Cs_2O = 0{\cdot}90\%$, $Rb_2O = 0{\cdot}03\%$.

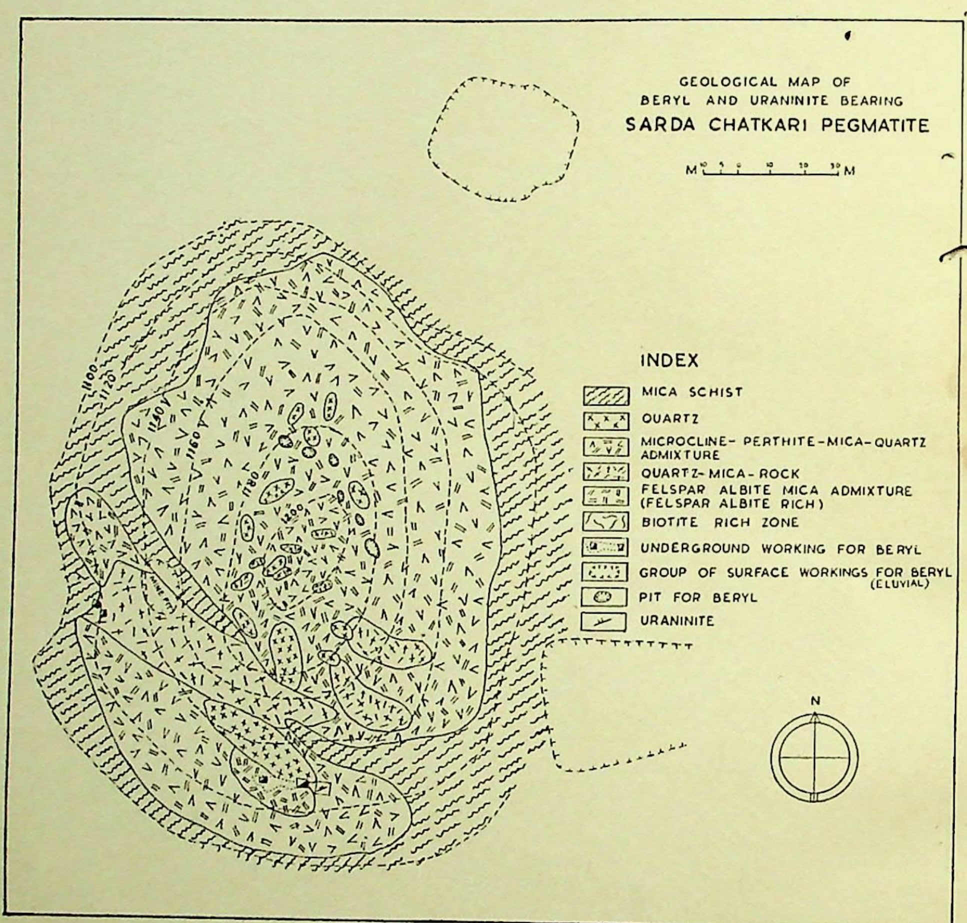

GEOLOGICAL MAP OF
BERYL AND URANINITE BEARING
SARDA CHATKARI PEGMATITE
M 10 5 0 10 20 30 M
INDEX
MICA SCHIST
QUARTZ
MICROCLINE- PERTHITE-MICA-QUARTZ ADMIXTURE
QUARTZ-MICA-ROCK
FELSPAR ALBITE MICA ADMIXTURE (FELSPAR ALBITE RICH)
BIOTITE RICH ZONE
UNDERGROUND WORKING FOR BERYL
GROUP OF SURFACE WORKINGS FOR BERYL (ELUVIAL)
PIT FOR BERYL
URANINITE
N
1100
1120
1140
1160
1180
1200

FIG. 5

It is significant that with the increase in alkali content both the BeO and the Al_2O_3 contents tend to decrease. For example, in the beryl from the Barakola pegmatite, having total alkali content of 3·65 ($Li_2O = 0{\cdot}91\%$, $K_2O = 0{\cdot}13\%$, $Na_2O = 1{\cdot}68\%$, $Rb_2O = 0{\cdot}03\%$ and $Cs_2O = 0{\cdot}90\%$), the BeO and Al_2O_3 contents are only 11·95% and 17·44% respectively, against which the Bhanakhap beryl with alkali content of only 0·33% contains 13·38% and 18·38% of BeO and Al_2O_3 respectively (Appendix III).

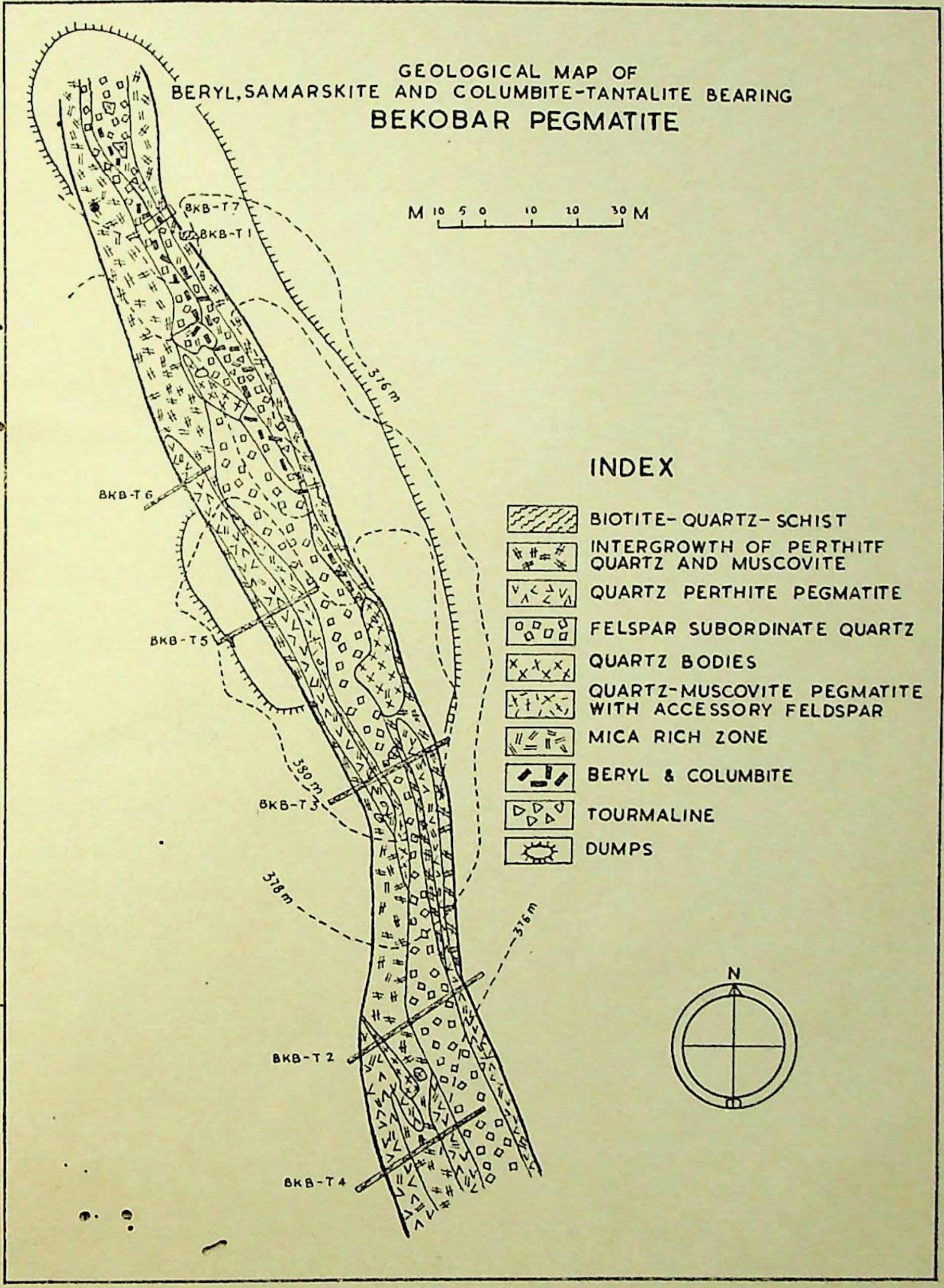

GEOLOGICAL MAP OF
BERYL, SAMARSKITE AND COLUMBITE-TANTALITE BEARING
BEKOBAR PEGMATITE
M 10 5 0 10 20 30 M
BKB-T7
BKB-T1
BKB-T6
BKB-T5
BKB-T3
BKB-T2
BKB-T4
376m
380m
378m
376m
INDEX
BIOTITE-QUARTZ-SCHIST
INTERGROWTH OF PERTHITF QUARTZ AND MUSCOVITE
QUARTZ PERTHITE PEGMATITE
FELSPAR SUBORDINATE QUARTZ
QUARTZ BODIES
QUARTZ-MUSCOVITE PEGMATITE WITH ACCESSORY FELDSPAR
MICA RICH ZONE
BERYL & COLUMBITE
TOURMALINE
DUMPS
N

Fig. 6

The Asarhua beryl with total alkali content of 1·64% (Na_2O = 0·92% and Li_2O = 0·45, Cs_2O = 0·26% and Rb_2O = 0·01%) is associated with low-grade green-coloured lepidolite with Li_2O content of less than 1%.

All the three sub-types of alkali-bearing beryls occur in replaced pegmatites, the last two with lepidolite and cleavelandite.

As beryl-bearing pegmatites have been worked only superficially and in a haphazard manner by private lessees who have unfortunately not maintained proper records of its production from individual mines and the total rock excavated, no reliable estimates of tenor of deposits are available.

The probable requirement of beryllium metal in India by 1970–71 and 1975–76 for beryllium-copper alloys, beryllium-aluminium alloys, ceramic industry, etc., has been estimated at 75 and 120 tonnes, which would (allowing for metallurgical and handling losses) respectively require 2,000 and 3,000 tonnes of beryl ore, ranging between 10 and 12% BeO. The requirement of raw material for the beryllium processing plant, when it is set up, would have to be met from the existing stocks of beryl and the current production which is mainly from the Bihar Mica Belt. If the above estimates of requirement of beryllium metal are correct, we can meet only a few years' requirement of the raw materials, after which the position will become alarming. Hence, not only all stocks have to be conserved for indigenous utilization but prospecting and exploration efforts need to be very much intensified right from now.

(ii) *Columbite-tantalite*

There are some 50 known occurrences of columbite-tantalite in this belt, (Appendix II), out of which nearly one-third are associated with small to moderate amounts of uranium; this number far exceeds the sum total of known occurrences from all the other parts of India. Almost half of the known occurrences are however only of a sporadic nature (Figs. 2, 3, 4, 6, 7 and 8).

In general, the columbite-tantalite occurrences in the Bihar Mica Belt are localized in four areas, viz. Bhanakhap-Pichhli-Ghortappe-Bendi in the west, Pihra-Satgawan-Chatkari-Manbhagwa in the mid-west, Khairadih-Bekobar in south-west and Bijaia-Batia-Asarhua-Amarjharna in the east, besides which there are a few sporadic occurrences at Goriadih, Doranda and east of Kaua Kol in the extreme north (Fig. 1).

The majority of these occurrences are of both the isomorphous oxide minerals, viz. columbite and tantalite, the total pentoxide content varying between 50·15% and 79·24%, the highest Cb_2O_5 content being 62·95% and the radioactive type also containing 0·01 to 2·40% U_3O_8. Practically all the consignments received are of columbite. Only solitary deposit of tantalite has been recently located at Khairidih (24° 26′ 35″ : 85° 37′ 47″), the analyses of representative consignment samples of which have ranged between 38·5–40·8% in Ta_2O_5, with 36·5% Cb_2O_5 and 0·18–0·19% U_3O_8. This pegmatite

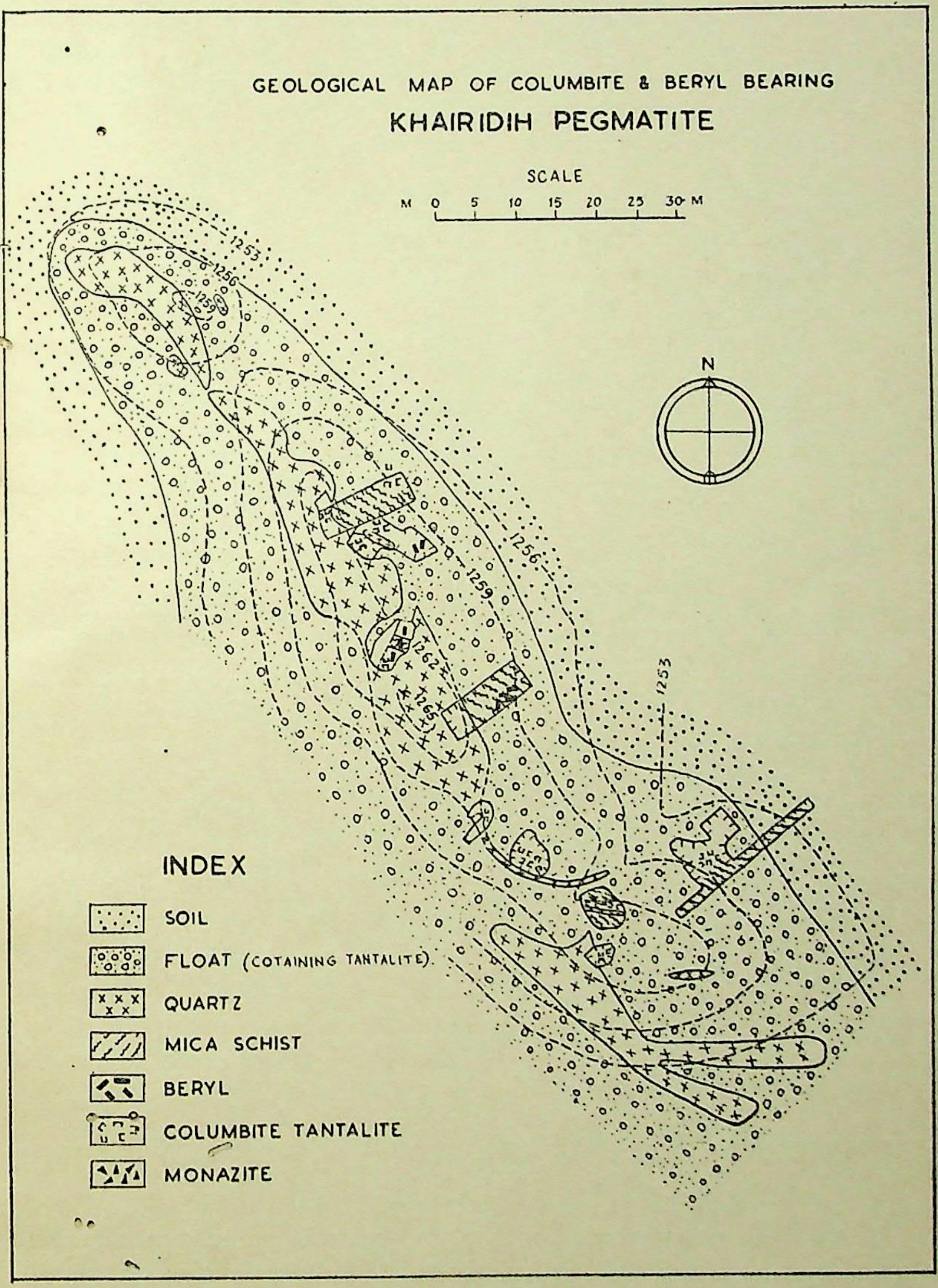


Fig. 7

has in the course of departmental working so far yielded about 2·5 tonnes of ore, which for such a type of deposit is considered a reasonably good production. The work is still in progress (Fig. 7).

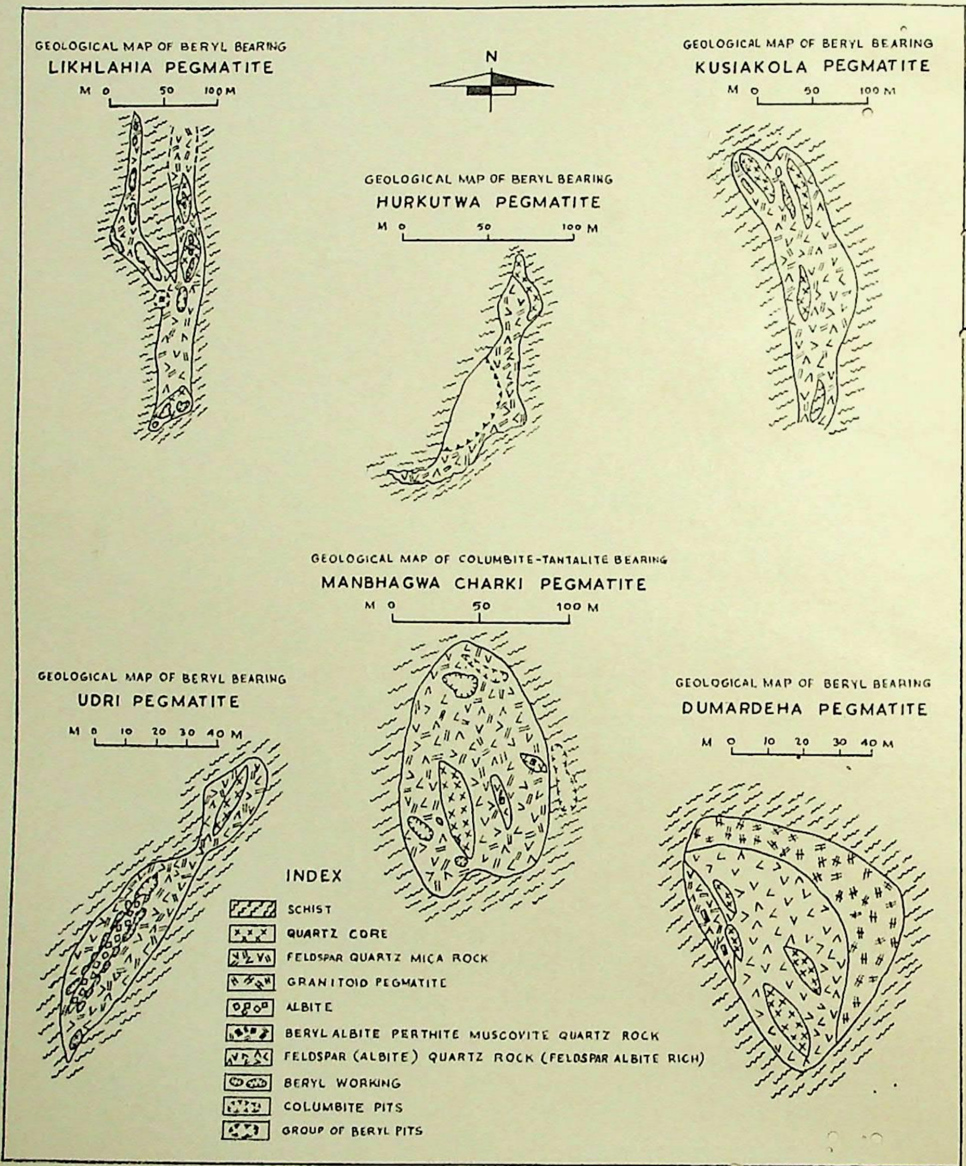
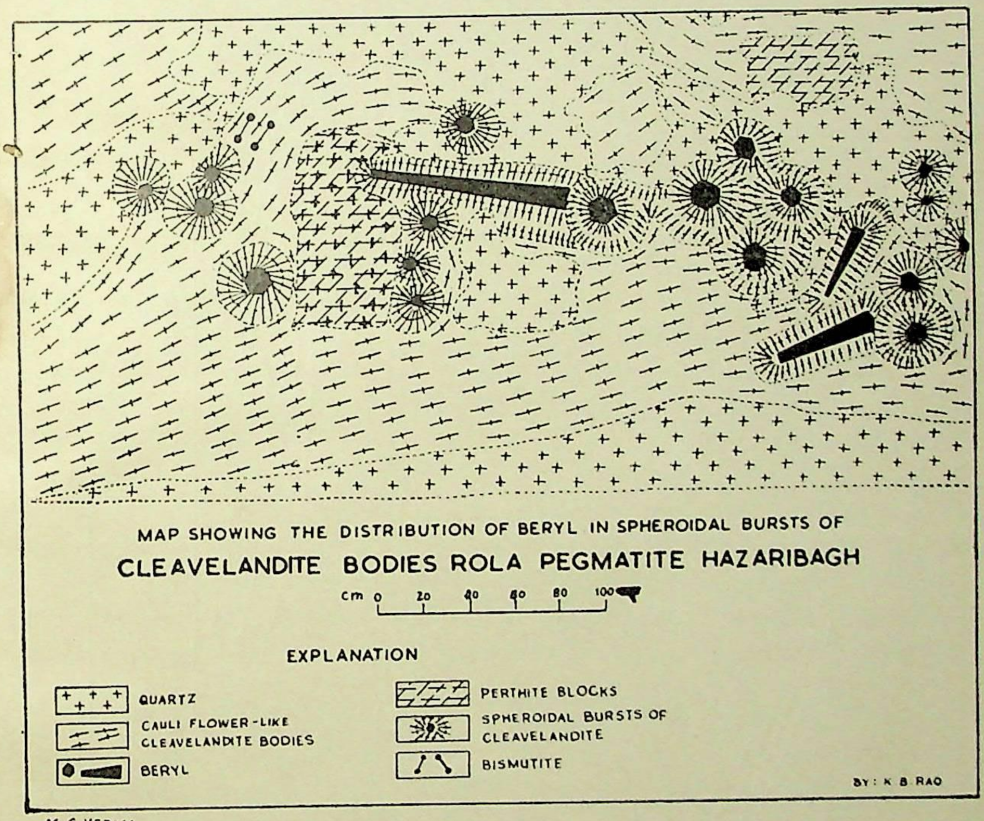

GEOLOGICAL MAP OF BERYL BEARING
LIKHLAHIA PEGMATITE
M 0 50 100 M
N
GEOLOGICAL MAP OF BERYL BEARING
KUSIAKOLA PEGMATITE
M 0 50 100 M
GEOLOGICAL MAP OF BERYL BEARING
HURKUTWA PEGMATITE
M 0 50 100 M
GEOLOGICAL MAP OF COLUMBITE-TANTALITE BEARING
MANBHAGWA CHARKI PEGMATITE
M 0 50 100 M
GEOLOGICAL MAP OF BERYL BEARING
UDRI PEGMATITE
M 0 10 20 30 40 M
GEOLOGICAL MAP OF BERYL BEARING
DUMARDEHA PEGMATITE
M 0 10 20 30 40 M
INDEX
SCHIST
QUARTZ CORE
FELDSPAR QUARTZ MICA ROCK
GRANITOID PEGMATITE
ALBITE
BERYL ALBITE PERTHITE MUSCOVITE QUARTZ ROCK
FELDSPAR (ALBITE) QUARTZ ROCK (FELDSPAR ALBITE RICH)
BERYL WORKING
COLUMBITE PITS
GROUP OF BERYL PITS

Fig. 8

It has been observed that in the west-central and eastern columbite-tantalite-bearing areas, and particularly in the former, deposits of lepidolite and beryl also occur. In some of the deposits columbite-tantalite is associated with samarskite or fergusonite as an intimate laminar intergrowth (annerodite). Intergrowths of columbite-tantalite, cleavelandite and garnet have also been observed, as in Rola pegmatite near Hazaribagh where cauliflower type cleavelandite and beryl also occur in the same pegmatite (Fig. 9). Encrustrations of autunite have also been observed on columbite-tantalite.

The Bihar Mica Belt has been a steady producer of columbite-tantalite, having contributed the major part of the country's production, but the average annual production for the last few years has been very low.


MAP SHOWING THE DISTRIBUTION OF BERYL IN SPHEROIDAL BURSTS OF
CLEAVELANDITE BODIES ROLA PEGMATITE HAZARIBAGH
cm 0 20 40 60 80 100
EXPLANATION
QUARTZ
CAULI FLOWER-LIKE CLEAVELANDITE BODIES
BERYL
PERTHITE BLOCKS
SPHEROIDAL BURSTS OF CLEAVELANDITE
BISMUTITE
BY: K B RAO

M.S.VERMA

FIG. 9

The private lessees are not showing much interest in working of columbite-tantalite-bearing pegmatites in their leased areas, as owing to its sporadic nature and abnormal increase in cost of mining they do not probably find it economical at the prevailing price of Rs.4 per kg. With the limited geological effort, it has not been so far possible to locate any large low-grade deposits of alluvial or eluvial nature or of the intergrowth type in pegmatites or of these minerals and pyrochlore-microlite in granites, carbonatites, etc. The present

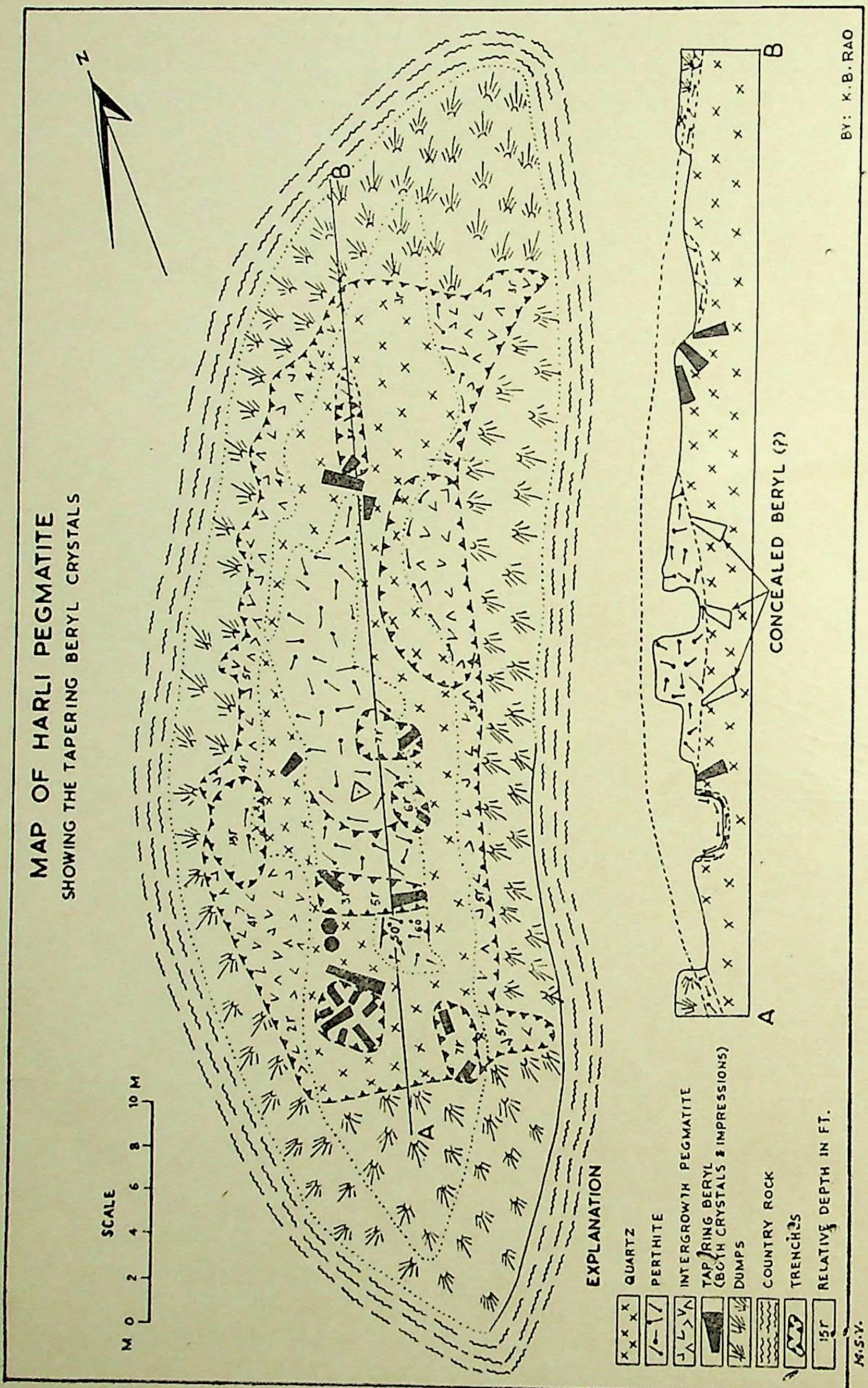

MAP OF HARLI PEGMATITE
SHOWING THE TAPERING BERYL CRYSTALS
N
SCALE
M 0 2 4 6 8 10 M
A
B
5'
4'
2'
3'
6'
10'
15'
16'
EXPLANATION
QUARTZ
PERTHITE
INTERGROWTH PEGMATITE
TAPERING BERYL (BOTH CRYSTALS & IMPRESSIONS)
DUMPS
COUNTRY ROCK
TRENCHES
RELATIVE DEPTH IN FT.
15'
CONCEALED BERYL (?)
A
B
BY: K.B. RAO
M.S.Y.

FIG. 10

stocks and production are also too meagre to meet a regular demand for many years to come.

There is definite and growing requirement for pure niobium and niobium-based alloys, among others, for radio-chemical nuclear fuel processing plant as cladding material for the metallic uranium fuel-element in high temperature fast reactors, or as Zr-2·5% Cb alloy as canning material in place of zircalloy and for alloy steel and in nuclear and electric industries. Tantalum is in great demand for defence and for capacitors required by the electronics industry, for which the annual requirement for the material has been estimated at 5 tonnes by 1975 by the Electronics Committee. Hence a very intensive programme of prospecting for deposits of columbium and tantalum and working the same is called for.

The reserves in the known deposits of columbite-tantalite down to easily workable depth may be of the order of a few hundred tonnes.

(iii) *Uranium minerals*

The uraniferous pegmatites were naturally the first to attract attention because of their containing well-developed and easily recognizable crystals of pitchblende or uraninite and a host of refractory and bright coloured secondary uranium minerals of high specific gravity.

About twenty-five uranium-minerals-bearing pegmatites have been located in the Bihar Mica Belt, out of which the majority, i.e. sixteen, carry refractory minerals: samarskite, euxenite and fergusonite, and uraninite is known from only three pegmatites, including the well-known occurrences of Pichhli and Bhanakhap (Abraki Pahar) reported by the Geological Survey of India 68 and 55 years ago respectively. Cyrtolite was observed only in the Sarda Mine in Chatkari area (Fig 5). Secondary uranium minerals, autunite, torbernite and gummite are reported from half a dozen localities (Appendix II).

Practically all these uranium-bearing pegmatites occur near the (*a*) Western (Bhanakhap-Pichhli-Ghortappe-Marhi Kalaunda Zone), (*b*) West Central (Chatkari-Manbhagwa-Dursahi-Khiri-kalan-Banga Khalar Zone) and (*c*) Southern (Bekobar and Doranda) parts of field, generally in close association with columbite-tantalite. The individual deposits occur near the margins of the various granite plutons (Fig. 1).

The uranium minerals occur in isolated pockets, invariably in zoned pegmatites, mostly in association with green interlocked mica, close to smoky quartz or in thin intergrowth (wall) zone close to the contact with the country rock. As with columbite-tantalite, the uranium mineralization appears to be associated with development of sugary albite and cleavelandite (Fig. 5).

At Ghortappe the radioactive minerals are associated with the mica zone near the hanging wall contact with the quartz core and in intermediate zone

(Fig. 2). At Doranda fergusonite occurs in the quartz-feldspar-mica intergrowth forming the wall zone following the microcline-perthite-albite zone outside the quartz core. The feldspar is kaolinized and the mica is of very poor quality. Large crystals of biotite also occur (Fig. 3).

Although uranium-bearing pegmatites are spectacular in yielding high-grade material, the occurrence of the mineral is highly sporadic and, as the pegmatites have a tendency to pinch out in depth, only small production varying from a few quintals to a few tonnes can be obtained from them as by-product during mining for other economic minerals.

Some of the samarskite- and fergusonite-bearing pegmatites are capable of yielding a few tonnes of a material containing 5 to 21% U_3O_8, e.g. the Doranda pegmatite has yielded over three tonnes of fergusonite ranging between 6·46–7·21% U_3O_8. The ores produced at Ghortappe, Bekobar and Banga Khalar have ranged between 12·55–21·10%, 17·78% and 6·22–10·10% U_3O_8, and euxenite from Pirvayya and autunite from Marhi Kalaunda 5·5% and 41% U_3O_8 respectively. The Indian production of this type has been supplied mainly from Bihar Mica Belt. In short, none of the pegmatites has so far been found to be rich and extensive enough to serve as a major source of supply of uranium for any extended period, and the total resources of this type are inconsequential.

(iv) *Lithium*

In the Bihar Mica Belt, large deposits of lithium occur almost exclusively as lepidolite and there is one solitary occurrence (Golgo) of amblygonite. Out of the total of some twenty-five occurrences known so far (Fig. 1), the largest concentration of lithium-bearing pegmatites is in the Charki-Manimahodar-Pihra and Gawan-Tisri zones, both situated in the central part of the belt, and the Bijaia-Asarhua-Lamki zone with a few stray occurrences in the eastern part of the belt. There are also two solitary occurrences from the western part of the belt at Pichhli (24° 35′ 58″ : 85° 26′ 24″) and Chatkari (24° 38′ 10″ : 85° 39′ 5″). The occurrences of Pihra and Manimahodar were located by the Geological Survey of India almost a century ago (Appendix II).

Lepidolite occurs mainly as scaly, flaky or granular aggregates, and only in a few cases it is of massive variety. There is one occurrence of foliated variety, in which lepidolite forms 1″ wide border on the outer edges of 4″ × 1″ book of muscovite. This suggests replacement of the latter by lepidolite.

Lepidolite shows much variation in colour from typical lilac or violet to mauve, pink, green, yellowish-green, bluish-grey, greyish-black and almost white. The lithium content ranges between 0·5%–5·4%, the highest value being from the eastern part of the belt in Monghyr district. Some of the low-grade material has been found to be lithium-bearing muscovite.

It has been observed that lepidolite rich in lithium has a lower refractive index than the poorer grade material. The greyish-black variety is probably zinnwaldite, but this needs confirmation.

Lepidolite invariably occurs in 'zoned' pegmatites, having a well-developed quartz core of white, rose or smoky colour, with which lepidolite occurs in intimate association either at its contact or in the adjoining intermediate zone consisting mainly of feldspars, viz. microcline perthite and also invariably cleavelandite or sugary, platy or other variety of albite.

Blue (indicolite), green and less commonly rose coloured (rubellite) or rarely even black tourmaline (schorl) appears to be a constant associate of lepidolite. The lepidolite-bearing pegmatites almost invariably carry beryl, which is generally rose coloured or white. Only in a few rare cases, columbite-tantalite has also been found to occur in such pegmatites, but this is by no means a universal association like that of lepidolite and beryl. Sometimes, such pegmatites also carry buckled green mica and garnet.

Several thousand tonnes of lepidolite, mostly of 2 to 2·5% Li_2O grade and above, have been produced out of which over 90% was contributed by the Bihar Mica Belt. This will be utilized for meeting indigenous requirement.

The over-all reserves of lepidolite available *in situ* down to economically quarryable depth and in the float are roughly estimated to be of the order of 10,000 tonnes. This may be much exceeded by underground mining in depth when there is demand for the ore. More precise assessment of reserves can, however, be done only by pitting, trenching and core drilling.

Although no high-grade ores have been so far located in this belt, there is a possibility that intensive search, including geochemical prospecting, may lead to locating large deposits of high-grade spodumene, petalite or amblygonite.

Ore-dressing tests have shown that lepidolite containing 2·7% Li_2O from this belt can be upgraded to 3·05% concentrate with 95% recovery by flotation at *p*H 3·5 using Armac 16 *D* as the collector.

The Central Glass and Ceramic Research Institute of Calcutta have shown some interest in indigenous lepidolite for the manufacture of lithium chemicals.

(v) *Caesium and rubidium*

Caesium and rubidium elements are invariably present in the beryl occurring in lithium-bearing pegmatites to the extent of 0·90 and 0·03% respectively. As these rare metals are in demand for the electronic industry, which is making rapid progress in India, it is proposed to analyse beryl samples from lithium-bearing pegmatites and if they contain significant percentages of these metals, it would be stockpiled separately to explore the possibility of their recovery at the time of manufacture of beryllium.

Simultaneously the caesium and rubidium contents of lepidolite and other minerals in such pegmatites would also be determined to ascertain whether any of them can serve as ore for these rare metals.

VI. PERSISTENCE OF ATOMIC MINERALS IN DEPTH

Practically all the mine owners have an impression that beryl and other atomic minerals in pegmatites occur only at or near the surface and do not persist in depth. Whereas in some cases the atomic minerals have been observed to persist down to about 100 m depth, in most cases with the splitting up and disappearance in depth of the quartz cores and replacement of the block microcline zone by intergrowth type of pegmatite and its lensing, the mine owner's fears of the atomic minerals getting depleted in depth appear to be justifiable. Of course, each case has to be examined on its merit to ascertain to what stage the pegmatite has been eroded by the weathering agencies; in those atomic-minerals-bearing pegmatites which are exposed above their middle portion, the minerals may be expected to persist to great depth.

Apart from this, at the outcrop of a pegmatite there is generally a good concentration of atomic minerals of eluvial origin*, representing the products of weathering of a large thickness of pegmatite which has been eroded away and consequent accumulation of the ores which are more resistant to weathering than the main constituents of the pegmatites.

VII. GENESIS OF ATOMIC MINERALS

The bulk of output of beryl is contributed by the alkali-free variety of green, blue or yellow-green colour which occurs as large euhedral prismatic hexagonal crystals at the contact of massive quartz core and the adjoining block microcline zone or in the latter. It appears to be of primary magmatic origin and occurs in earlier-formed microcline perthite-quartz pegmatites of zoned type.

On the other hand, the alkali beryls, which contribute a comparatively lesser proportion of production, occur as shorter subhedral to euhedral prismatic crystals or irregular aggregates of paler shades of green, blue, yellow or of white colour, in pegmatites which have been replaced by hydrothermal action of the resultant fluids and which crystallized at a later stage. The latter type of mineralization appears to be responsible for the albitization of microcline giving rise to fine-grained sugary albite, fine laminated albite and cleavelandite together with some muscovite.

The author is inclined to agree with Mahadevan and Maithani (1967) that in this belt muscovite crystalized in two generations, viz. the earlier formed one occurring as large books of commercial mica and subsequently formed one as interlocked or wedge-shaped green mica which is universally associated with beryl and other atomic minerals. Pure aggregates of muscovite were also deposited along fracture planes during the later stage.

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* For example eluvial beryl at Phaguni Mine and eluvial columbite-tantalite at Manbhagwa and Goriadih and eluvial lepidolite at several places.

The pegmatites of this belt appear to have been evolved in an open system in stages by the overlapping influx of potash rich and soda rich solutions. In the final predominantly sodic phase, the solution and its volatile contents rich in lithium, beryllium, etc., remaining till late stages of hydrothermal differentiation of this magma, were injected in the already solid portion of the pegmatite intrusion in one or more phases. They were responsible for emplacement of lepidolite, beryl of second generation and cleavelandite pegmatite by matasomatic replacement or auto-metasomatism of microcline. This explains the erratic occurrence of these minerals, especially lepidolite.

The occurrence of abundant topaz in the western part of the belt shows significant role of fluorides in the emplacement of beryl.

Sometimes the cleavelandite development may be only local or no beryl or lepidolite may be associated with it.

The zonal arrangement of inclusions of feldspar, mica, tourmaline, etc., in a 'shell beryl' shows that it was the product of replacement during the later stages. In some beryl crystals fractures are found to have been healed with quartz, etc., of a later generation.

VIII. Geochemical Prospecting for Atomic Minerals

As a result of working during the past 30–35 years, the mining/quarrying of even some of the outstanding deposits of beryl is already becoming uneconomical, and it is anticipated that practically all the known deposits may get exhausted within the next few decades, say by the turn of the century. However, the demand for the strategic metals beryllium, niobium and tantalum is bound to increase appreciably, particularly for the aircrafts and space ships, hence we have to plan for sources of supply.

Our search for non-pegmatitic beryllium in India has so far not met with any success. Such deposits are not always easy to distinguish by the naked eye, particularly because the veins containing beryl and bertrandite are generally friable and easily get disintegrated into fine rubble and soil. For inexpensive reconnaissance for demarcation of the areas most favourable for further work, the geochemical method of prospecting for niobium, tantalum, beryllium, etc., based on analyses of soil samples, which have been tested with positive results in different tropical and sub-tropical regions, would be suitable for Indian conditions.

The concentration of beryllium in the soil or alluvium is generally less than 5 ppm, so that addition of a few minute fragments of a beryllium mineral can increase the tenor of a sample by an amount readily detectable by spectrographic and fluorimetric analyses.

The soils derived from the metamorphic rocks may contain only 2 to 3 ppm of Be; that derived from granite may contain as much as 10 ppm. Near beryllium-rich parts of veins, which weather readily, however, the alluvium may contain 10 ppm or even up to 100 ppm in the richest samples from areas which drain beryl-bearing rocks.

It has been observed that the coarser (over 200 mesh) fractions of alluvium contain more beryllium over the beryllium-rich granite or pegmatites than elsewhere, but the finer fraction contains a rather uniform 2 to 5 ppm in most places sampled over the stock.

It has also been found that analysis of alluvium is an effective and relatively economical way to demarcate areas in which beryllium-rich rocks lie buried and that any area should be considered favourable if it yields samples containing 10 ppm or more Be, but even values between 5 ppm and 10 ppm may be promising in samples taken from geologically favourable places.

Analyses of residual soils can, therefore, serve as a useful guide in locating individual bodies of beryllium-rich rocks in the same way that float has long been used in finding veins.

Like uranium, lithium is generally a mobile element which becomes widely dispersed. It has been used as a pathfinder element for mineralized pegmatites.

The columbium and tantalum are heavy, rather resistant minerals with low mobility and they give rise to persistent drainage anomalies.

Another line of approach for geochemical prospecting for beryl and columbite-tantalite, which has given promising results, is study of their primary dispersion in the associated muscovites.

In regions containing deposits of beryllium minerals, the soils get enriched in beryllium and relatively high Be content (up to 0·01%) is found in ashes of the plants growing in the regions of beryllium-bearing pegmatites.

Geochemical prospecting can also help in locating concealed or blind pegmatites which do not outcrop.

IX. OUTLOOK FOR ATOMIC MINERALS IN BIHAR MICA BELT

The Bihar Mica Belt has abundant deposits of atomic minerals, viz. beryl, columbite-tantalite, etc., in pegmatites spread all over the belt. Most of the easily accessible ores have been recovered by the lessees, the majority of whom now do not take interest owing to the sporadic nature of occurrences, a marked rise in the cost of mining and the low margin of profit left to them at the prevailing prices in comparison to that in mica mining. The deposits are, however, by no means exhausted and the resources of beryl ore still available would possibly be of the order of at least 20,000 tonnes, though it may be possible to win it at a higher price than in the past.

Efforts are being made to work the unleased promising deposits of columbite-tantalite and beryl departmentally, side by side with guiding and encouraging the lessees to step up production from their lease areas. It is hoped that they will feel enthused by the upward revision of the price of beryl ore from Rs.75/- to Rs.88/- per unit tonne of beryllium oxide content and this would give a fillip to its production.

There are chances of discovery of additional deposits of beryl and columbite-tantalite and of higher grade deposits of lithium at the outcrops and also in the alluvium-covered areas if an intensive drive is made, aided by geochemical prospecting. There are also chances of finding large low-grade deposits of beryllium and columbium-tantalum in or around the belt, provided necessary additional geological and other effort becomes available.

It is expected that the Belt will be able to adequately meet the country's requirement of beryl, columbite-tantalite, lithium minerals, etc.

Thus, it would be seen that the rich and promising Bihar Mica Belt is bound to play an important role in the nuclear power programme and for other peaceful uses of atomic energy in India.

DISCUSSION

Questioner's Name: Dr. K. K. Majumdar

Question:

We have found that minerals procured for stock-piling by AMD are not fully analysed and also localities not noted. In one case we found that low-grade columbite-tantalite ore stock-piled contains about 55·0% tin oxide. The locality could not be ascertained and thus we missed a very important source of tin ore.

Author's Reply:

The elements to be analysed and the methods of stock-piling depend upon the policies of the Department which cannot be discussed here.

Among the pegmatitic minerals, besides beryl, we were interested only in columbite-tantalite, uranium ores and lithium minerals, and although cassiterite was detected by us, it could not be purchased by this Department as it is not an atomic mineral.

Dr. Majumdar is probably not aware that sporadic pockets of such minerals occurring in pegmatitics cannot be a worthwhile source of tin, which is derived in commercial qualities either by dredging of coastal marine sand or beach deposits or by hydraulicking or hydraulic mining of large deposits of tin-bearing kaolinized granites.

Questioner's Name: Dr. S. Deb, Jadavpur University.

Question:

Whether Microlite-Pyrochlore minerals can be distinguished from columbite-tantalites.

Author's Reply:

Yes; they can be distinguished by microscopy, X-ray and chemical composition. The morphology is also different.

ACKNOWLEDGEMENTS

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APPENDIX I

LIST OF IMPORTANT BERYL-BEARING PEGMATITES IN BIHAR MICA BELT

Gaya District: Singar area (Bhanakhap, Pichhli, Hirakhan mines), Chatkari area, (Manbhagwa, Phagunia-Kararua, Likhlahia, Kusiakola), Gaighat.

Hazaribagh District: Bendi area (Lalki, Ranikola Chowkiatanr mines), Khaira Chori Chatan, Bekobar (Dumardiha), Inderwa, Kakoria-Thimya, Dhab area (Deghi, Thakani, Dhajwa, Belopahari, Charka-pahari mine), Gawan area (Harharia mine), Satgawan area (Khiri kalan, Nagri, Jogidih, Angar, Donai). Tisri area (Ghortia mine, Chandori, Damelwa, Khatponk, Narayanpur, Kulmangri), Barakola Pahari, Jamhara, Rangamatia, Baramasia, Charki-Balbali, Dumbla, Bishunpur, Duba, Khiri-khurd, Suyari Pahari, Kewariadih.

Monghyr District: Dhanwe, Charkapathal area, Kodwatanr, Lamki, Asarhua, Jerwanari, Konjhi, Bhulki Mine, Maheshwari area, Chakai area (Jhalki mine), Batia area (Ranipahari, Batahana Pahar, Jherulia, Bandarchuwa mine).

APPENDIX II

LIST OF OCCURRENCES OF ATOMIC MINERALS OTHER THAN BERYL IN BIHAR MICA BELT

I. URANINITE/PITCHBLENDE: Abraki Pahar (Bhanakhap), Pichhli and Sarda (Chatkari).

II. SAMARSKITE, FERGUSONITE, AMPANGABEITE AND EUXENITE:

Gaya District: Manbhagwa, Pichhli and Sarda (Chatkari), Gaighat.
Hazaribagh District: Ghortappe, Doranda, Khiri Kalan (Pihra), Bekobar (Dumardiha), Bangakhalar, Dursahi and Pirvayya.
Monghyr District: Kewal, Amarjharna, Goriochun, Kurwa and Karia Pathar.

III. AUTUNITE, TORBERNITE AND GUMMITE: Abraki Pahar, Sarda, Pichhli, Manbhagwa, Bagra and Marhi Kalaundi.

IV. CYRTOLITE: Sarda (Chatkari).

V. COLUMBITE-TANTALITE (Uraniferous):

Gaya District: Pichhli and Manbhagwa.
Hazaribagh District: Ghortappe, Doranda, Tilaiya, Khiri Kalan (Pihra) Karbe-Khurd, Dhab and Jhorijh, Goriadih.
Bhagalpur District: Bagra, Mathabari, Satletwa, Titibaran, Ukharia, Taragachha and Dokhri.

VI. COLUMBITE-TANTALITE (non-uraniferous).

Gaya District: Chatkari Kararua, Manbhagwa.
Hazaribagh District: Bekobar, Bangakhalar, Doriathari, Khairidih, Dhajwa, Chokiatanr (Bendi), Angar (Satgawan), Barakola Pahari, Phaguni mine near Dubaur, Bhanakhap, Kewariadah, Likhlahia, Dokari, Jahusbera, Nunibasa, Manu Pahari, Ninu Pahari, Niru-Pahari, Nandih, Dhanharwa Pahari and Dumardiha, Rola. Ekbanwa v. near Jorasemar.
Monghyr District: Bhaluwahi area, Kaunji-Pahari, Lakhan Kiari, Kodwatan, Amarjharna, Bijaiya, Panmannia, Asarhua.

VII. LEPIDOLITE:

Gaya District: Pichhli.
Hazaribagh District: Bhuladih, Dhanharwa, Duba (Charki), Nagri, Basodih, Sankh, Jogidih, Manimohodar, Khiri Kalan (Pihra) Surangi

Pahari and Barakola Pahar, Khakriar, Balbali, Bullibandh, Baramasia, Patna and Gutiya. –

Monghyr District: Bijaiya, Dhalai-Pahari, Ghuntia mine, Naguan, Lamki hill, Asarhua.

VIII. AMBLYGONITE:

Hazaribagh District: Golgo (near Tisri).

APPENDIX III

Analyses of samples of beryl from the Bihar Mica Belt

Radicals	Bhana-khap Mine (Gaya Dt.)	Asarhua Mine	Bara Kola (Charki-Surangi) (Hazaribagh Dt.)	Rola (Hazaribagh Dt.)
SiO_2 %	64·64	63·68	62·76	63·54
BeO %	13·38	12·58	11·95	13·25
Al_2O_3 % ..	18·38	18·31	17·44	18·60
Total iron as Fe_2O_3 % ..	0·18	0·32	0·09	0·75
CaO %	0·66	0·37	0·74	Practically Nil
MgO %	0·47	0·35	0·80	1·26
Li_2O % ..	Nil	0·45	0·91	–
Na_2O % ..	0·30	0·92	1·68	0·65
K_2O %	Nil	Nil	0·13	Practically Nil
Rb_2O % ..	0·001	0·01	0·03	–
Cs_2O % ..	0·03	0·26	0·90	–
H_2O %	0·92	1·10	0·67	1·52
Loss on ignition other than water % ..	1·12	1·38	1·87	
	100·081	99·73	99·97	99·57

Analyses by Dr. V. T. Athavale and other officers of Analytical Division, Bhabha Atomic Research Centre, Bombay.

LIST OF PAPERS ACCEPTED FOR PUBLICATION IN THE SUBSEQUENT ISSUES OF THE 'PROCEEDINGS OF THE INDIAN NATIONAL SCIENCE ACADEMY', PART A

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Super-radiant Lasers *by* B. M. Sivaram

Optical Pumping—a Formalism and Proof *by* B. S. Mathur

Photographic Materials and Coherent Light *by* P. Hariharan

Ultra-short Pulse Lasers *by* D. D. Bhawalkar

Principles of Raman-Lasers and Parametric Amplifiers *by* Sudhanshu S. Jha

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Use of He-Ne Lasers for Alignment *by* D. Sen

The Mega Structures in the Recent Sediments of the Tay Estuary, Scotland *by* S. K. Mishra

On the Evaluation of Three-centre Hellmann-Feynman Force Integrals Involved Stater-type Atomic Orbitals *by* B. M. Deb

Uranium Deposits in Singhbhum and Their Development of Use in the Nuclear Power Programme in India *by* K. L. Bhola

Petrographic Study of Two Flows of Picrite-Basalt from the Igatpuri Area, Maharashtra State *by* K. K. Mishra

Uranium Mineralization in the Pelitic Schists in the Kulu Himalaya and its probable Origin *by* G. R. Narayan Das, T. N. Parthasarathy *and* P. C. Taneja

On the Origin of Beryllium Mineralization around Burha Pahar Batholith near Kunkuri (District Raigarh, Madhya Pradesh) *by* G. S. Bhatnagar

Location of Graphite Deposits by Self-potential Method around Persia and Mahugain, Palamau District (Bihar) *by* C. L. Singh *and* Avadh Ram

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